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ADVANCES IN PHYSICS

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EDITORIAL NOTICE

THIS and the following issue of " Advances in Physics " contain a symposium of the papers delivered at the International Conference on Rock Magnetism, in the Department of Physics at Imperial College, London, during November 1956. The Conference was held under the auspices of the International Union of Pure and Applied Physics, and under the chairmanship of Professor P. M. S. Blackett, F.R.S.

J. A. CLEGG,
Department of Physics,
Imperial College, London,

Introductory Remarks

By P. M. S. Blackett

This first International Conference on Rock Magnetism is being held under the auspices of, and has been financially supported by, the International Union of Pure and Applied Physics. Though the subject which we are here to discuss during these three days is a new one to many of us, it has in fact quite a long history, extending back over almost half a century. It is fitting that we should remember at the outset the work of the pioneers such as Brunhes, Koenigsberger, Chevallier, Mercanton, Théllier, Kato, Nagata, Johnson and McNish, to mention only a few, who made important contributions in the early days.

The two main objectives of contemporary studies of Rock Magnetism seem to me to be its use as a tool for the investigation, on the one hand, of Polar Wandering and Continental Drift, and, on the other, of the History of the Magnitude and Direction of the Earth's Magnetic Field. In saying this I am relegating the detailed study of the physio-chemical mechanisms, by which the magnetism is produced, to the role of a means to these two ends rather than to that of an end in itself, although, of course, these mechanisms form a fascinating and important field in their own right.

If it is indeed true, as many of us here including myself believe, that the study of the magnetism of rocks from different parts of the globe has already made it appear probable that both Polar Wandering and Continental Drift have occurred, and that further work in the next few years will either confirm these preliminary findings in detail for refute them *in toto*, then it behoves all workers in the field to exercise an especial sense of responsibility as regards claims for the reliability of deductions from our experimental results. For the truth or falsehood of the old hypotheses of Wandering and Drift is not the private preserve of these engaged exclusively in Rock Magnetism: on the contrary, these hypotheses long preceded our activities, and any successful test of their truth or falsehood by palaeomagnetic measurements will inevitably cause some drastic rethinking in many branches of geology, geophysics, palaeontology and palaeoclimatology. We must guard ourselves against letting our legitimate excitement at our emerging experimental evidence lead scientists in these other fields up any unnecessary garden paths.

It seems to me also that the same caution is eminently desirable in the interpretation of the palaeomagnetic evidence concerning the history of the earth's magnetic field. If the postulated reversals are indeed real, then this fact will dominate all future theories of the detailed origin of the field, and will be sufficiently important to justify a massive onslaught, involving perhaps many thousands of hours of computing machine time, on the problem of seeking a possible mechanism for a self-reversing, self-excited fluid dynamo. Personally, I do not hold that the evidence, strong as it is, is as yet conclusive enough to justify such a bold theoretical programme. However, I am convinced that several more years of intensive experimental work will surely suffice either to prove that reversals have indeed taken place, and if so to elucidate the phenomenological details of the process, or, alternatively, finally to prove that they have not.

By bringing together so many active workers in Rock Magnetism from so many lands to discuss one other's results, it may be hoped that some definite steps forward will be made towards the solution of these two main objectives. Some contributions from some participants in this Conference may appear amateurish to others present. This is inevitable in a subject such as this, which impinges on so many other scientific fields. In principle, the rock magnetic worker should have a detailed knowledge of many parts of stratigraphy, structural geology, petrology, palaeontology, palaeoclimatology, crystal physics, ferromagnetism, and theories of the internal dynamics of the earth. Since this is obviously impracticable, he must inevitably rely on advice from experts in these various fields, to whom he must often appear amateurish in his use of their work. It is hoped that this Conference will do something to bring all these diverse disciplines together for our common purpose.

Palaeomagnetic Measurements on Karroo Dolerites

By K. W. T. Graham and A. L. Hales
Bernard Price Institute of Geophysical Research University of the Witwatersrand, Johannesburg

§ 1. Introduction

In 1955 the authors started on a programme of measurement of the direction of magnetization of the sedimentary rocks of the Karroo system. In selecting specimens for palaeomagnetic measurement it is necessary to avoid regions of dolerite intrusion in view of the possibility of the sediments being baked by such intrusions. It is well known that there are extensive dolerite intrusions in the Karroo system north and east of the line marked on the 1939 edition of du Toit's map (du Toit 1939) as the southern limit of the Karroo dolerites, but omitted from the 1954 edition. Dolerites of possible Karroo age do occur south of this line but comparatively infrequently. However, in this southern region the Karroo sediments have been affected by the Cape folding and in some cases show evidence of shear. Thus, these rocks too, must be used with caution for palaeomagnetic measurements.

In view of the dolerite difficulty it became clear that it was desirable to measure the direction of magnetization associated with the dolerites at an early stage. The first collection of 30 dolerite samples from 13 sills and dykes exposed in road cuttings and quarries was made in December 1955 during a visit of Dr. John W. Graham of the Department of Terrestrial Magnetism, Carnegie Institution of Washington. On a later trip the authors collected a further 17 samples from 7 similar fresh exposures and six additional samples from a sill sampled during the first trip. The results of this survey were disappointing in that they showed considerable scatter. Remeasurement after a period of seven or eight months showed that the scatter could be considerably reduced by the elimination of the samples which were demonstrably unstable. Details of the measurements of the surface samples will be given in § 6 of this paper.

In the meantime measurements had been made on underground samples from two localities viz : (*a*) from the shafts of Winkelhaak Gold Mine to the east of Johannesburg and (*b*) from a railway tunnel near Estcourt in Natal. The scatter in the underground samples was considerably less than that in the surface samples as had been found by Gough (1956) in a similar survey of the Pilansberg dyke system.

§ 2. Method of Collection

In general the sample collected is in the form of a one inch diameter cylinder some five or six inches long. This is drilled *in situ* using a portable diamond coreing drill driven by a small petrol engine. The principal difficulty in drilling away from road transport is that a minimum of two gallons of water is required to drill a six inch core. A line is scratched down the length of the core while still *in situ* and the bearing of this line and the inclination of the axis of the cylindrical core in two directions are determined by means of a Brunton compass. The top and bottom of the core are carefully marked.

In the first collection of dolerites oriented hand samples were chipped from the rock and drilled in the laboratory. A similar procedure was used by the staff of the Geology Department of Union Corporation in collecting samples from the shafts of Winkelhaak mine.

Usually four or five specimens in the form of cylinders one inch in diameter and one inch long are cut from each sample whether it is drilled *in situ* or in the laboratory.

§ 3. METHOD OF MEASUREMENT

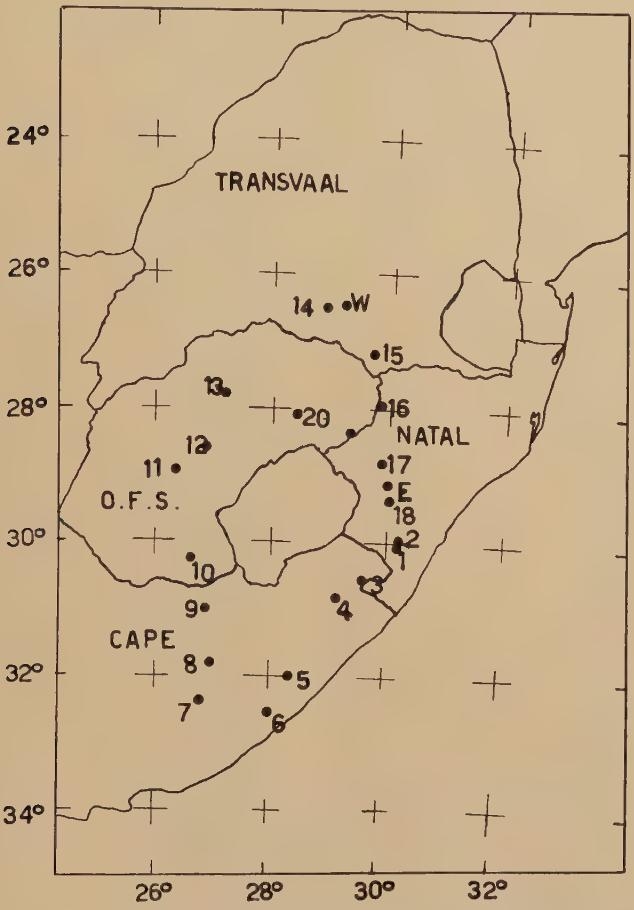
The instrument used for measurement is a spinner type magnetometer similar to that described by Graham (1955). In this type of magnetometer a signal from the coils, generated by the spinning specimen, is compared in phase with that received by a photoelectric cell from a paint pattern on the spinning top. In the system as devised by Graham the signals from the coils and the photoelectric unit are fed through carefully matched narrow band pass filters before they are compared in a phase discriminating circuit. For the early measurements reported here a circuit involving only one filter unit was used. The signals from the coil and the photoelectric unit were mixed before filtering. If the signal from the photoelectric unit be adjusted until it is equal in amplitude but opposite in phase to that from the coils, then the resultant signal received from the filter will be a minimum. The filter unit in this case functions as a null detector. This method works very well down to intensities of magnetization of the order of 10^{-6} c.g.s.u. giving an accuracy at this level of better than 2 or 3 degrees. However, as the signal approaches noise level, the accuracy with which it is possible to set to a minimum falls rapidly so that the system containing two separate filters, as used by Graham, is very much more convenient for measuring weakly magnetized specimens. The Department of Terrestrial Magnetism, Carnegie Institution of Washington, has very kindly lent us a pair of their matched filter units and the instrument was modified to operate in the Graham manner before measurements were made on the specimens from the Winkelhaak shafts and the Estcourt tunnel.

§ 4. MEASUREMENTS OF UNDERGROUND DOLERITES FROM WINKELHAAK, NEAR KINROSS, TRANSVAAL

Oriented samples were very kindly collected for us by geologists of Union Corporation during the course of shaft sinking operations at Winkelhaak Mines Ltd. on the Far East Rand. The position of the mine is marked as 'W' on the map of the Eastern half of the Union shown in fig. 1. Two pairs of vertical shafts were sunk, the members of a pair being approximately 750 feet apart and the distance between the pairs about one mile.

Two dolerite sills intruded into Lower Karroo (Ecca) sediments, were intersected in the shafts. The upper sill extends from the surface to a depth of between 70 and 80 feet. The lower sill, occurring at a depth of about 630 feet, is about 50 feet thick. Seventeen samples, subsequently cut into 57 specimens, were collected from the upper sill, while 8 samples, cut into 33 specimens came from the lower sill.

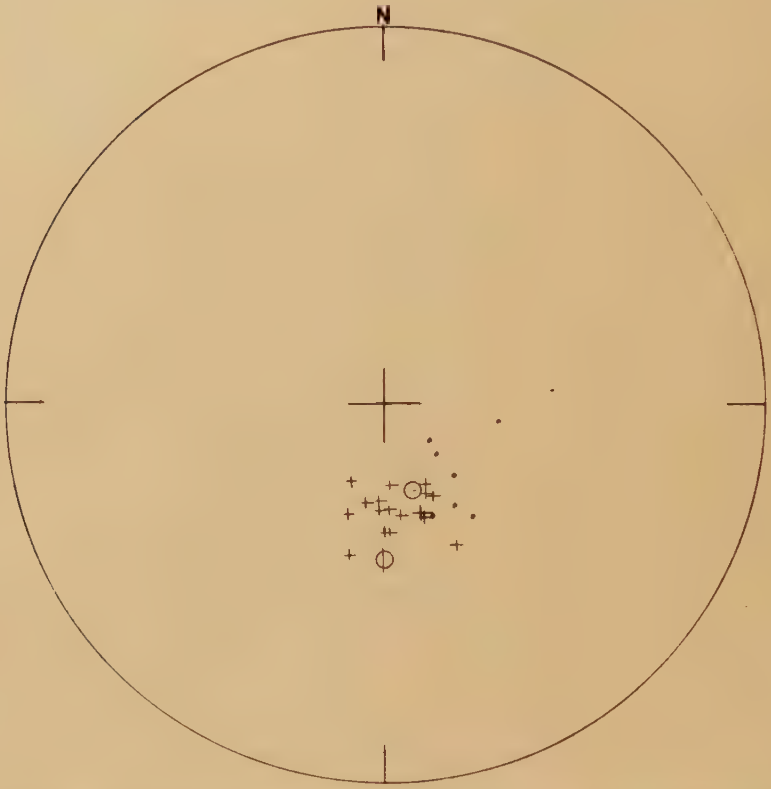
Fig. 1



The Eastern half of the Union of South Africa. The numbered points indicate the localities at which surface samples were collected. 'E' and 'W' indicate Estcourt and Winkelhaak respectively.

All specimens from the upper sill were magnetized with the north seeking poles downwards, i.e. in the reverse direction to the present field, whereas all specimens from the lower sill had the south seeking pole downwards, i.e. are magnetized in the normal sense. The results of these measurements are shown in fig. 2, a stereographic plot of the lower hemisphere. It should be noted that the directions found for the upper and lower sills are not exactly reversed relative to each other. The directions of magnetization of the samples from the lower sill have steeper dips and lie farther east than those of the upper sill.

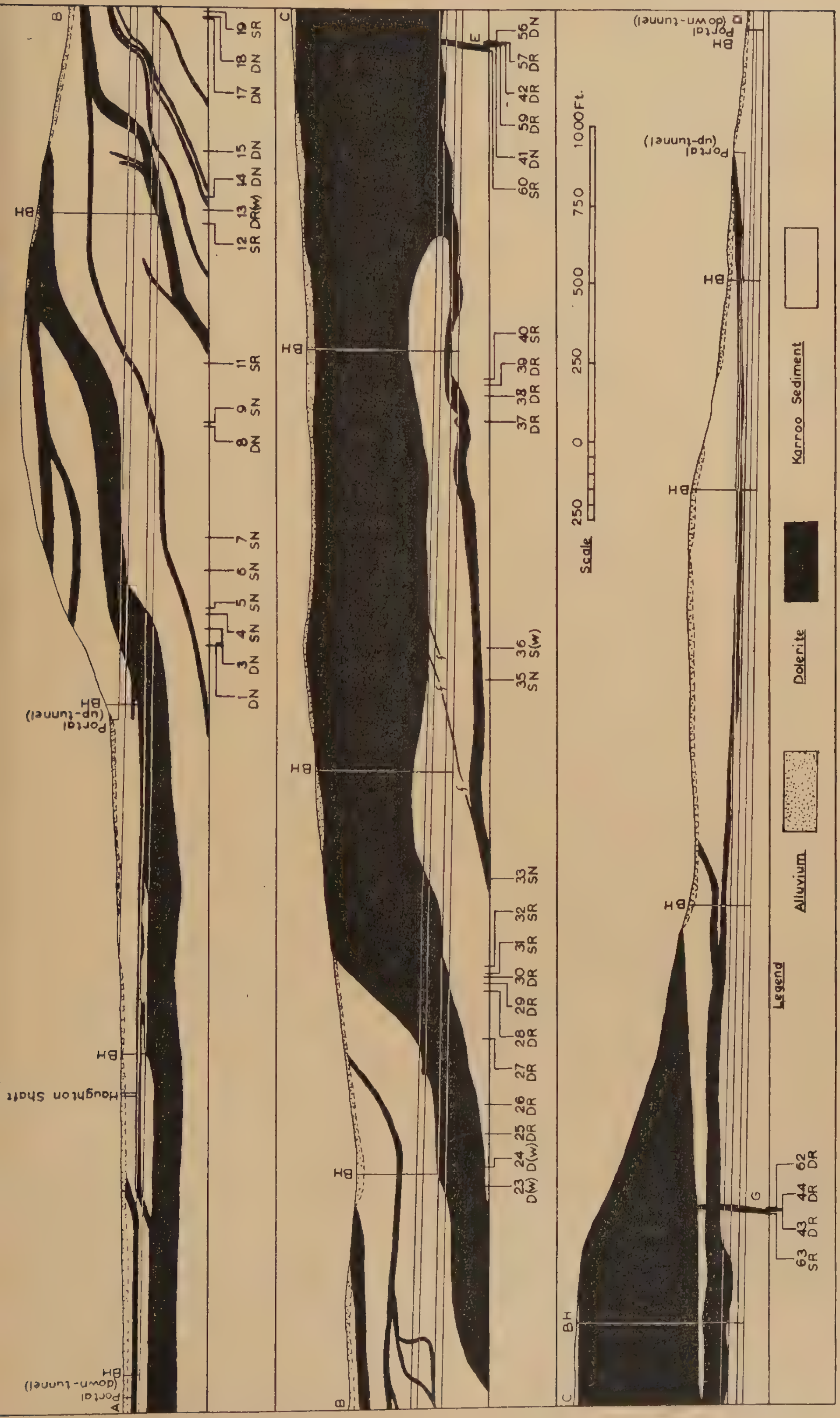
Fig. 2



Directions of magnetization of the dolerite samples from Winkelhaak plotted on the lower hemisphere of a stereographic net.

• South-seeking poles (lower sill).
+ North-seeking poles (upper sill).
○ Present field.
Φ Axial dipole field.

The statistics for these samples are given in table 1. In calculating the mean directions, sample means were first calculated from the directions of the individual specimens. These sample means were then used to calculate the mean for the group, giving each unit weight. If the measurements on each specimen had been given unit weight the circle of 95% confidence would have been much smaller but it is doubtful whether directions found from several specimens cut from the same sample can be regarded as independent measurements in terms of sampling the dyke or sill as a whole.



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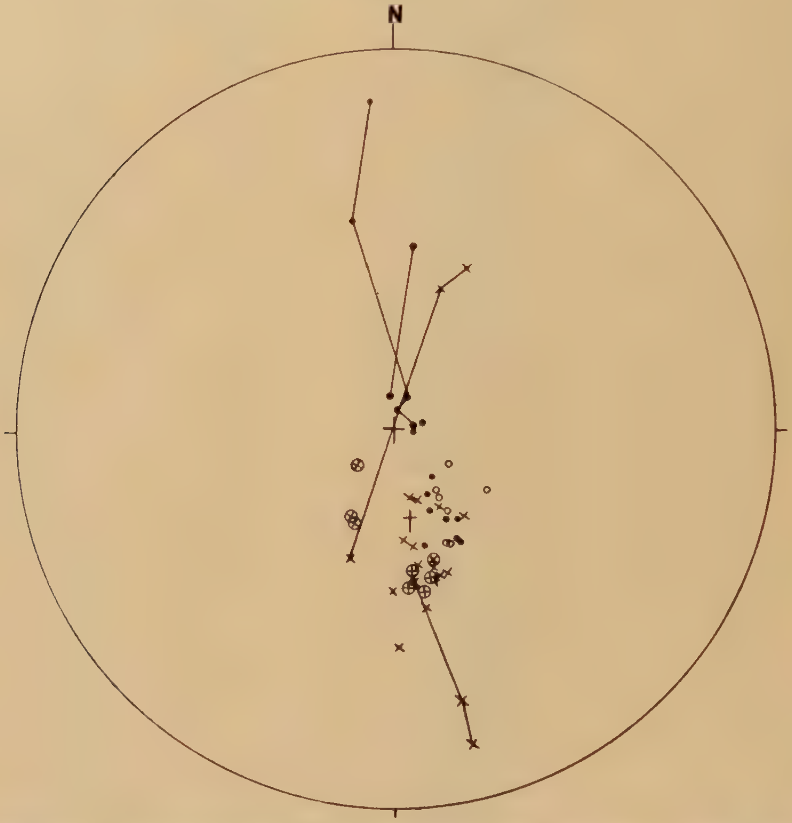
A geological section of the environs of the tunnels near Estcourt. The samples were taken from the lower tunnel vertically above the points indicated by numbers.

D=Dolerites; S=Baked sediments; N=Normally magnetized; R=Reversely magnetized; (W)=Scattered.

§ 5. MEASUREMENTS OF UNDERGROUND SAMPLES FROM A RAILWAY TUNNEL NEAR ESTCOURT, NATAL

A geological section of the tunnel environs, prepared by Mr. P. J. Smit of the Geological Survey, is shown in fig. 3. The samples were taken from the lower tunnel vertically above the points indicated by numbers on the diagram. Dolerite and baked sediment samples are distinguished by ' D ' and ' S ' respectively while ' N ' indicates that they were magnetized in the normal sense and ' R ' in the reversed sense. In the case of four samples (13, 23, 24, 36) the individual specimens from a single sample form a streak instead of a fairly tight group. These are indicated by ' W '. The directions of magnetization are plotted on the lower hemisphere of a stereographic net in fig. 4. For the four samples showing the

Fig. 4



Directions of magnetization of the samples from the tunnel near Estcourt plotted stereographically on the lower hemisphere. Individual specimens from a single sample showing a streak are joined by a line. Otherwise sample means are plotted.

● = Normally magnetized dolerites; × = Reversely magnetized dolerites; ○ = Normally magnetized baked sediments; ⊕ = Reversely magnetized baked sediments; † = Direction of the present field of the earth.

streaking the directions of magnetization of the individual specimens have been plotted, those from the same sample being linked by a line. The rest are shown as the mean for the sample, calculated from several specimens.

Examination of the data in fig. 3 shows that in general the baked sediments are magnetized in the same sense as the adjacent dolerites. There are, however, some anomalies.

When the first collection was made two samples (41, 42) were taken from the dyke at point E. One of these (41) was found to be magnetized in the normal sense, the other in the reversed sense. It was decided to return to the tunnel to collect additional samples from this dyke. (The other anomalous regions had already been cemented up.) These samples served to show that the chill zones were normally magnetized, whereas the interior of the dyke and the only sample of baked sediment that was measurable, were magnetized in the reversed sense. Possible explanations of this are :

(*a*) that the chill zones are unstable ;

(*b*) that a self-reversing mechanism operates in the chill zones ;

(*c*) that a self-reversing mechanism operates in both the interior of the dyke and in the adjacent sediments but not in the chill zones ;

(*d*) that a reversal of the earth's field occurred while the dyke was cooling ;

(*e*) that there is in fact more than one intrusion with a reversal of the earth's field between the intrusions.

The possibilities (*c*), (*d*) and (*e*) seem unlikely. On the information available at present it is impossible to decide between (*a*) and (*b*), though the possibility of instability in some samples of dolerite is supported by the streaking noted in samples 13, 23 and 24.

Table 1

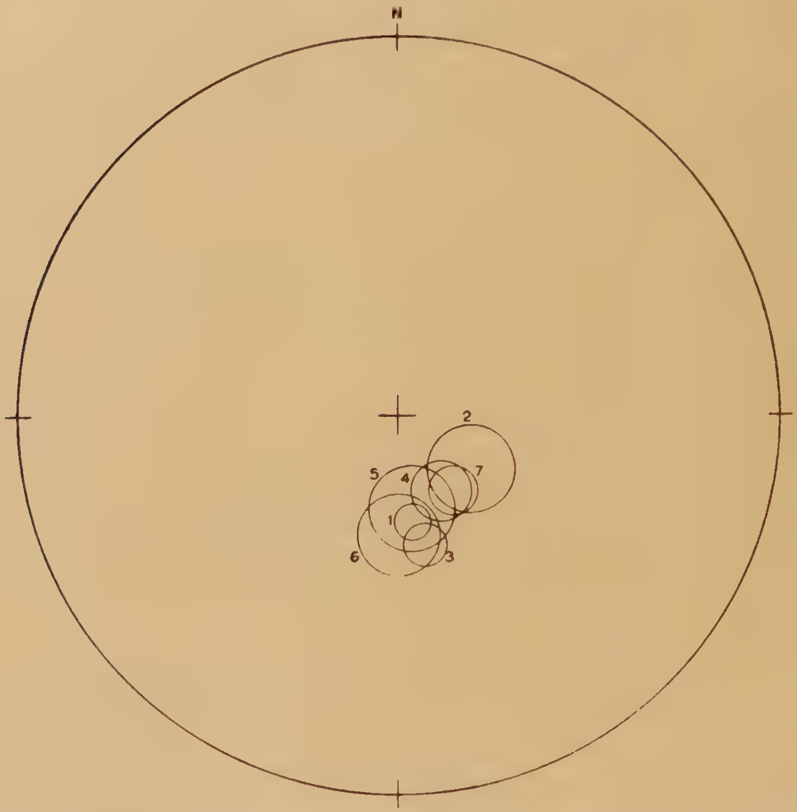
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Latitude of collection point	26·5°S	26·5°S	29·1°S	29·1°S	29·1°S	29·1°S	30·3°S
Longitude of collection point	29·1°E	29·1°E	29·9°E	29·9°E	29·9°E	29·9°E	28·5°E
Number of samples	17	8	15	8	9	7	33
Number of specimens	57	33	53	25	34	24	149
Mean declination, D	173°E	127°E	167°E	180°E	151°E	144°E	172°E
Mean dip, I	58°	63°	51°	55°	64°	62°	62°
Semi-vertical angle of 95% confidence, α †	5°	12°	6°	11°	8°	7°	12°
Geographic pole	77°S	44°S	77°S	—	67°S	—	76°S
Geographic longitude of pole	53°E	82°E	90°E	—	94°E	—	52°E
δp	6°	14°	6°	—	10°	—	14°
δm	7°	18°	8°	—	12°	—	19°

(1) Winkelhaak upper sill ; (2) Winkelhaak lower sill ; (3) Estcourt reversed dolerites ; (4) Estcourt reversed sediments ; (5) Estcourt normal dolerites ; (6) Estcourt normal sediments ; (7) Surface collection.

† Calculated by Fisher's Method (1953).

Considering the results from this tunnel as a whole, mean directions calculated from the reversely magnetized dolerites, the reversely magnetized sediments, the normally magnetized dolerites and the normally magnetized sediments are given in table 1. Samples 13, 23, 24 and 36 have been omitted from these calculations. The difference between the sediments and the dolerites is in all cases within the limits of error of the means, whereas the mean for the normally magnetized samples is significantly different from that of the reversely magnetized group. This point is clearly shown in fig. 5, a lower hemisphere stereographic plot showing the 95% confidence circles for the four groups of specimens from Estcourt and the two groups from Winkelhaak. It will be noted also that the Winkelhaak reversed samples do not differ significantly from the

Fig. 5



Stereographic projection on the lower hemisphere showing the circles of 95% confidence of the mean values for (1) Winkelhaak reversed dolerites, (2) Winkelhaak normal dolerites, (3) Estcourt reversed dolerites, (4) Estcourt normal dolerites, (5) Surface dolerites, (6) Estcourt reversed baked sediments, (7) Estcourt normal baked sediments.

Estcourt reversed samples nor do the Winkelhaak normal samples differ significantly from the normal Estcourt samples. All the normally magnetized samples do, however, differ significantly from the reversed ones. It may be expected that, in view of the possible instability of some of the normally magnetized samples, the mean for these samples might not be as satisfactory a datum as that found from the reversely magnetized ones. In the case of the latter it is considered that the fact that they have retained a direction of magnetization which is in the opposite sense to the present field is in itself an assurance of their stability.

Inspection of fig. 4 reveals that, although the normally magnetized samples give magnetic directions closer to the present field of the earth than do the reversed ones, they all lie off to the East, and it seems unlikely that they are all unstable. Furthermore, it is difficult to see why, in general, the baked sediments should only be unstable close to dolerites that are unstable. Similarly, it seems unlikely that a self-reversal mechanism should affect dolerites and their baked sediments in some areas while those in other areas should be unchanged.

The explanation of these observations would seem to be complex. It seems probable that these intrusions are not strictly contemporaneous and the possibility of a reversal of the earth's field during the time of intrusion of this swarm of sills and dykes must be considered. Perhaps samples 13, 23 and 24 happened to be cooling through their Curie points at the time of the reversal of the field. If we assume that such a reversal did take place, we would have a picture of normally magnetized sills and dykes with normally magnetized adjacent sediments and reversely magnetized dolerites with their reversed baked sediments. Secondary effects, due to self-reversal under special circumstances or to instability, might be superimposed on the simple picture.

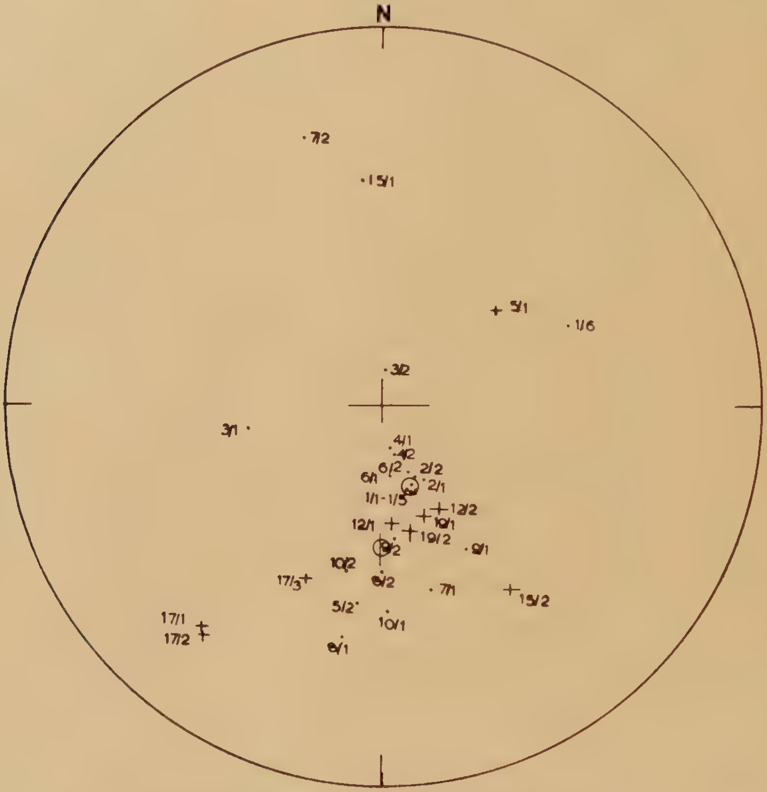
§ 6. THE MEASUREMENTS ON THE SURFACE SAMPLES

The localities from which the samples were collected are indicated by numbers on a map in fig. 1. All the surface samples were measured as soon after collection as possible. One specimen from each sample was remeasured three or four months later and another specimen from each was remeasured some seven or eight months after the first measurements. It was found that some specimens showed a considerable change from the direction of magnetization first measured and it seems reasonable to conclude that those specimens for which the change was considerable are unstable. It was decided to exclude all samples from a locality if any one of the specimens remeasured had shown a change in the direction of magnetization of more than 10 degrees. The sample means for the remaining samples are shown in fig. 6. It will be noted that there are still a number of scattered measurements but in such cases the two samples from the same locality do not agree and they, too, may be unstable. The mean for the surface collection was calculated disregarding sign and giving unit weight to each sample and is given in table 1. As will be seen from a plot of this mean and its circle of 95% confidence (fig. 5) the surface samples are not inconsistent with the Winkelhaak or Estcourt groups.

§ 7. Discussion

All samples discussed in this paper were taken from intrusions in sediments of Karroo age, or from the sediments themselves. There is no doubt that the intrusions can be classified as Karroo dolerites. These dolerites have been studied extensively by Walker and Poldervaart (1949).

Fig. 6



Directions of magnetization of the surface dolerites plotted stereographically on the lower hemisphere.

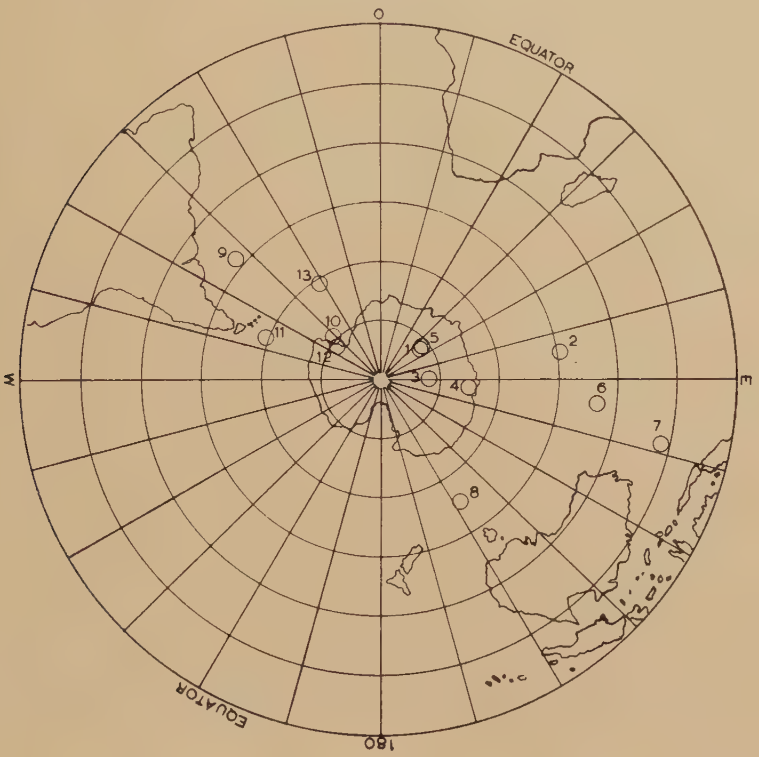
• = Normal sense ; + = Reversed sense ; ⨀ = Present field ; ⏀ = axial dipole field.

(17/2 indicates the mean direction of magnetisation of specimens from sample 2 taken from locality 17.)

They consider that the Stormberg lavas were poured out towards the close of Triassic time and that the dolerites were more or less contemporaneous with the lavas. Du Toit (1954) remarks also that there is an intimate connection between the Stormberg basalts and the dolerites and concludes that the dolerites appear to have been intruded at the commencement of the Jurassic epoch.

The positions of the magnetic poles corresponding to the mean directions of magnetization found in §§4, 5 and 6 have been calculated on the assumption that the field at the time was a dipole field. These values are given in table 1 together with quantities δp, δm, the semivertical angles of the oval cone of 95% confidence (Irving 1956 a). These positions have been plotted in fig. 7, an azimuthal equidistant projection of the southern hemisphere. Also plotted in fig. 7 are pole positions inferred in similar manner from measurements on specimens from England, North America, India and Tasmania. Details of ages and authorities are given in table 2.

Fig. 7



An azimuthal equidistant projection of the southern hemisphere showing the poles calculated from palaeomagnetic data from various parts of the world. (See table 2.)

It will be seen that the pole positions inferred from the measurements on the South African dolerites are not consistent with any of those found for rocks of the same age in Europe, North America and Australia. If it be assumed that the direction of magnetization, when averaged over the time of intrusion of these dolerites, is a slowly and smoothly varying function of time then the simplest way of reconciling the divergent pole positions is to postulate relative displacement of the continents, i.e. Continental drift. It is noteworthy that the displacements required are of the kind proposed by Wegener (1924), du Toit (1937), King (1953) and Carey (1955).

It should be noted, however, that there is some evidence that the assumption of a slowly varying direction of magnetization is an over-simplification. Clegg *et al.* (1956), point out that the lavas from the Khandala region are younger than those from Linga. Since the Khandala measurements give a pole position nearer to India than do the Linga measurements, this means that either the drift pattern was complicated, or that there was polar movement of some 20 degrees between the times of intrusion of the two series of lava flows. It is interesting to note that the difference in the direction of magnetization of the reversed and normal South African dolerites is indicative of a fairly rapid movement of the pole or of the continent.

Table 2

1. Winkelhaak upper sill—Jurassic.
2. Winkelhaak lower sill—Jurassic.
3. Estcourt, reverse sense—Jurassic.
4. Estcourt, normal sense—Jurassic.
5. Surface collection—Jurassic.
6. Linga area, late Cretaceous to early Eocene, Clegg *et al.* (1956).
7. Khandala area, early Eocene, Clegg *et al.* (1956).
8. Tasmanian dolerite, probably Jurassic, Irving (1956 b).
9. Keuper marls, Triassic, Clegg *et al.* (1954).
10. Antrim lavas, Eocene, Hospers and Charlesworth (1954).
11. Arizona, Triassic, Runcorn (1955).
12. Colorado plateau, Cretaceous, Runcorn (1955).
13. Maryland, Triassic, J. W. Graham (1955).

It is clear that more accurately dated measurements covering a larger proportion of the stratigraphic column than are at present available are required in order to establish with certainty whether or not the present misfit of palaeomagnetic data is due to imperfect correlation. Only then will one be able to describe with any confidence the possible drift paths followed by the continents.

ACKNOWLEDGMENTS

It is with pleasure that we acknowledge our indebtedness to the many people who have assisted us in the work reported in this paper. Our thanks are due especially to Dr. Merle A. Tuve, Carnegie Institution of Washington, for the loan of the narrow band filters ; Dr. John W. Graham for much helpful advice on spinner magnetometers and palaeomagnetism generally ; Mr. A. Frost, Consulting Geologist, Union Corporation and Mr. E. F. Marland and the staff of the Union Corporation Geology Department for the collection of the Winkelhaak samples ; Dr. F. C. Truter, Director Geological Survey, Dr. L. E. Kent and Mr. P. J. Smit for geological information about the railway tunnel near Estcourt; Mr. A. Goldstein, Chief Civil Engineer, South African Railways and Harbours, Messrs. Rand Earthworks Ltd., for permission to collect specimens in the tunnel; The South African Council for Scientific and Industrial Research, for a grant for a research assistant; Mr. R. Green, who made many of the measurements and Mr. J. A. Keiller and Mr. J. Magee of the Bernard Price Institute workshop who built the equipment.

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Palaeomagnetic Collections from Britain and South Africa Illustrating Two Problems of Weathering.

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§ 1. Introduction

In much of Northern Europe and North America the problem of surface weathering tends to be ignored because of the comparatively fresh outcrops which are relics of the Ice Age. The surface of Africa however has been exposed since at least early Tertiary times and perhaps even earlier, and has been subjected to two or three cycles of erosion. In a continent where large areas are almost without exposure, and where artificial exposures are few, collections are obviously restricted and in consequence an understanding of the effects of weathering is of great importance. Weathering effects can be illustrated by reference to two sets of results, those of the Lower Jurassic Karroo basalts, and of the Upper Triassic Sandstones.

The state of the original iron ore detrital minerals in a sedimentary rock is controlled in part by pre-depositional weathering, and the extremely low intensities of many pale coloured sediments may not so much due to their lower iron ore content but rather to the physical state of these minerals. This is illustrated by reference to Jurassic and Cretaceous arenaceous rocks.

§ 2. Post Depositional Weathering

Specimens of Karroo basalts were obtained from the neighbourhood of Bulawayo where three flows were sampled, and from the area of Victoria Falls, where five or possibly six flows were sampled. The former set were all either from surface outcrops or shallow road cuttings, and the latter from deep quarries and from the second gorge below the Victoria Falls. When palaeomagnetic measurements were made it was found that, with the exception of one locality, samples from surface exposures gave extremely scattered results with marked inconsistencies occurring between individual cores from the same specimen (see fig. 1†), and one specimen was so highly magnetic that it was suspected of having been struck by lightning. On the other hand the samples from the gorge and deep quarries gave results which clustered closely together.

The Upper Triassic Cave Sandstone of Bechuanaland was extensively collected with the help of Mr. Green of the Bechuanaland Protectorate Geological Survey. This sandstone when obtained fresh from a borehole is a bright red in colour, comparable to that of the Permo-Triassic deposits of this country. One collection made by Green in the Kgomo dia Tshaba valley was of rather weakly coloured material showing secondary silicification. The scattered results obtained lie in the N.W. quadrant (see fig. 2) and give a mean close to that of the Karroo basalts. From other localities more normally coloured specimens gave results which differed markedly from the Kgomo series, though they are themselves scattered. Similar scattered results are available from the coeval Forest Sandstone from Southern Rhodesia and when the two series of results are combined (fig. 3) there appears to be a definite spread of negative dips along a line N60E–S60W. Such scattering seems to be characteristic of few other sediments which have been measured to date.

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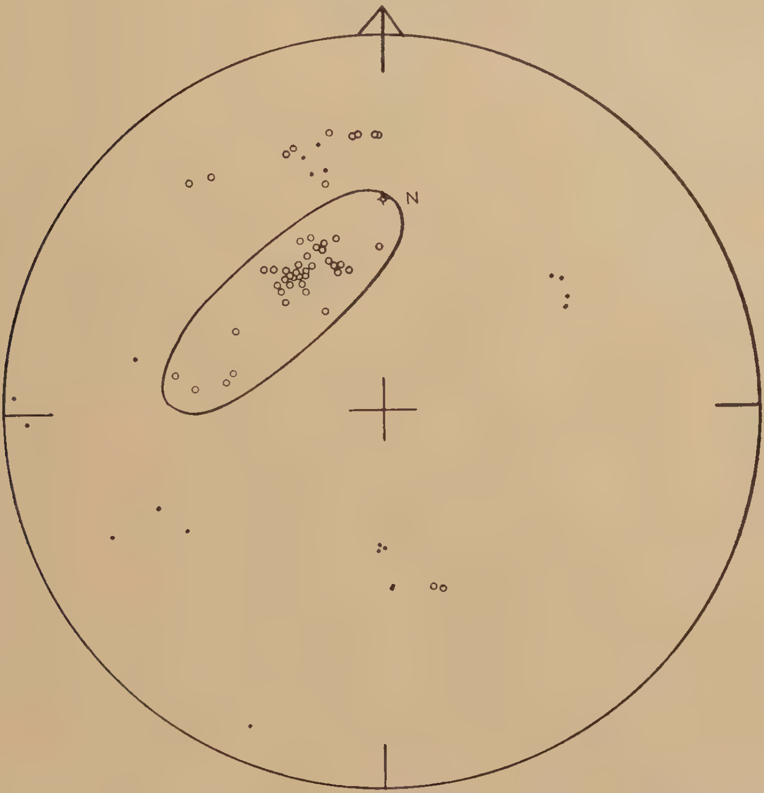
† In all diagrams, North seeking poles pointing down are marked by •; North seeking poles pointing up are marked by ∘; and the axial dipole field by -ϕ- or + in the northern hemisphere.

Stereographic polar projections are used throughout.

Fig. 1



Direction of magnetization of Karroo basalt specimens from Victoria Falls and Bulawayo.

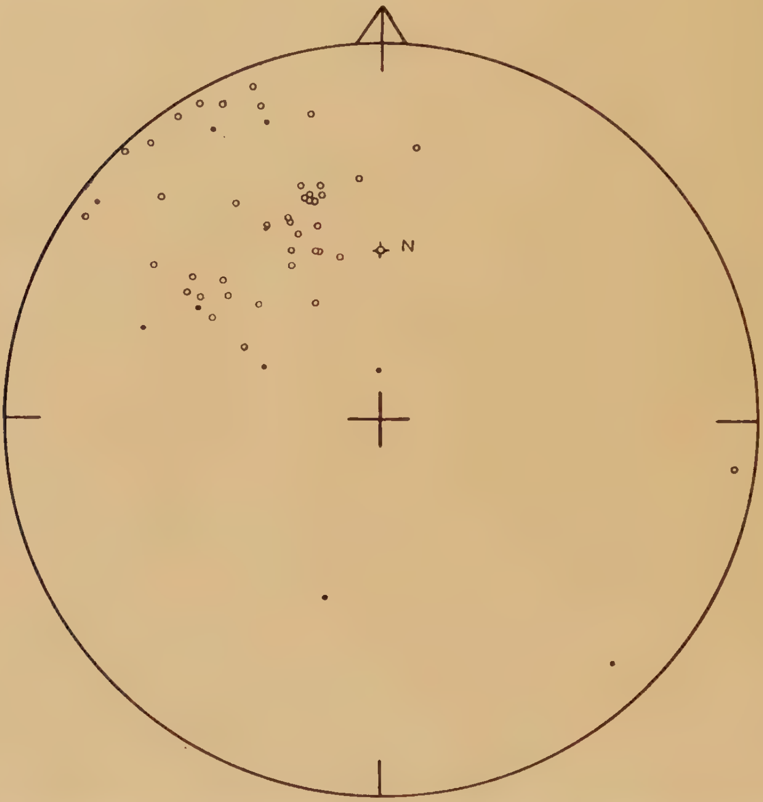
Bk1, Bk2, Bk3, flows from Bulawayo ; 1, 2, 3, 4, flows from Victoria Falls ; M.C., flows from quarries near Victoria Falls.

While the weathering processes have not been studied in detail they are undoubtedly in part of a chemical nature, and it is suggestive that these unreliable rocks, whose directions of magnetization are either scattered or convergent on the present pole position, are obtained from surface outcrops even when the material may appear quite fresh. It seems possible that the IRM (iso-thermal remanent magnetization) component by means of which Runcorn (1956) explains the great-circle distribution of results from some sediments collected in the southwest of the U.S.A., may, in part at least, be due to weathering at surface outcrops.

§ 3. PRE-DEPOSITIONAL WEATHERING

The empirical generalization that drab coloured sediments are unsuitable for palaeomagnetic work has been generally accepted for a number of years, and probably as a consequence of this, such rocks have been little studied. In view of the stratigraphical importance of the Jurassic and Cretaceous periods in any consideration of the dual problems of Polar Wandering and Continental Drift, especially in the light of the succession of determined pole positions, a detailed sampling programme of the drab

Fig. 2

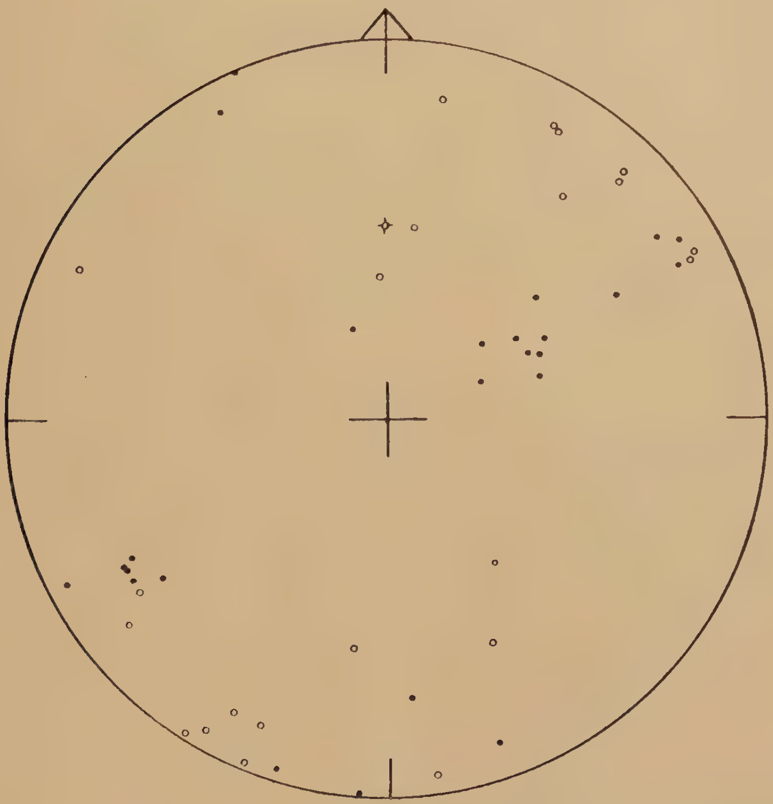


Direction of magnetization of Cave Sandstone from Kgomo Dia Tshaba, Bechuanaland.

arenaceous sediments within the Jurassic and Cretaceous was nevertheless carried out. Samples were collected from Eastern and Western Scotland, Yorkshire, the Wealden district, and Northern France. The majority of these samples proved to be either too weak for measurement or unstable.

The iron ore minerals of representative samples were analysed, the iron ore minerals being extracted from bromoform-separated, heavy mineral fractions, by means of an electromagnet or by hand-picking. The iron ores were x-rayed, and gave rather diffuse lines suggestive of goethite.

Fig. 3



Direction of magnetization of Cave and Forest Sandstones from Bechuanaland and Southern Rhodesia.

The interstitial iron ore, often powdery and yellowish in colour was in the 'limonitic' form (Posnjak and Merwin 1919).

The Jurassic and Cretaceous arenaceous sediments are deltaic deposits where sedimentation was comparatively rapid. It therefore seems likely that the detrital iron ore minerals were deposited in the goethite condition, and consequently hydration had occurred before transportation. This agrees with the grain shape and the fact that the beds may show current bedding and do not show reworking. It has been shown (Moore and Maynard 1929) that iron whether carried in colloidal or true solution is normally precipitated in the limonitic form (microcrystalline goethite with absorbed water).

While the above considerations account adequately for the palaeomagnetic unsuitability of drab coloured deltaic sediments, they are incomplete and even misleading unless the climatological conditions are explicit, for the preceding remarks relate specifically to a cool temperate climate. This may at first seem at variance with the known warm late Mesozoic climate, with the sporadic development of coral reefs and even some coal in the Jurassic. However the sediments in question were derived from the north and from a higher altitude and hence must belong to a cooler environment.

Thus the full conclusion is that drab deltaic sediments of *a cool environment* are palaeomagnetically unsuitable. It is possible that, under cold conditions where chemical weathering is to a large extent inhibited and subordinate to mechanical weathering, deltaic sediments with unaltered iron ore minerals could be formed. The Lower Ecca Sandstones may belong to this category. In a hot climate the mode of formation of drab deltaic deposits is less obvious.

§ 4. PALAEOMAGNETIC RESULTS

The only satisfactory result from the African collections to date are from the Karroo basalts (Nairn 1956) mentioned earlier which with a pole position (latitude 2 N, longitude 8 W) in Hudson Bay, indicate a movement of the order of 2000 miles since early Jurassic times. For the

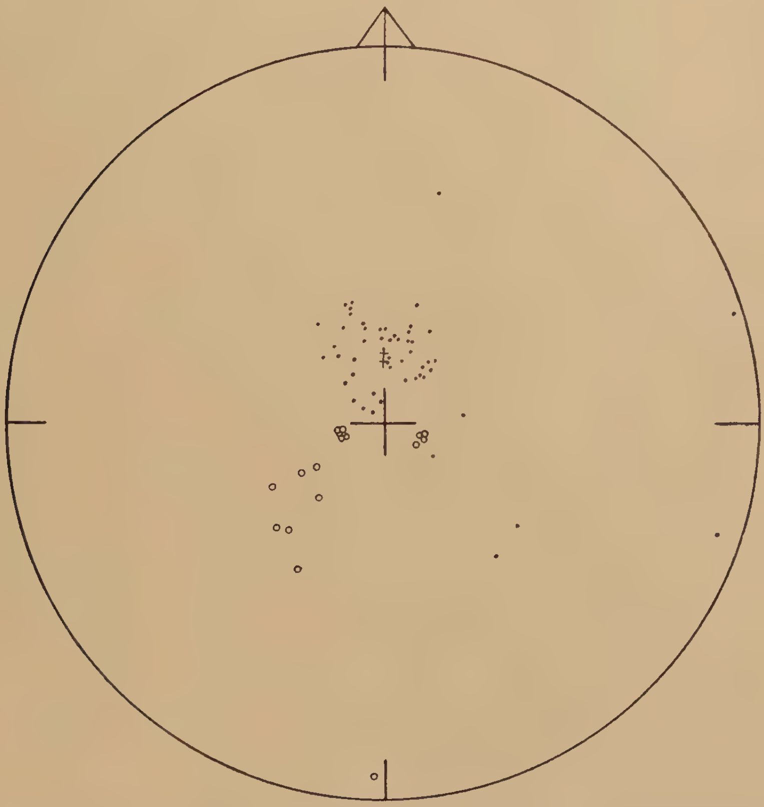
	I	II	III	IV	V	VI
	Declination East of N. D	Inclination I	Number of discs N	Number of specimens S	α†	*k*‡
Scotland Jurassic	226°	–65° Up	14	4	6·6°	33·4
Rhodesia Jurassic	332°	–40° Up	44	11	4·6°	18·7
Bechuanaland Triassic	326°	–16° Up	44	8	9·5°	6·14

† α=radius of 95% circle of confidence, calculated by Fisher's Method (1953).
‡ Fisher's *k* value.

late Triassic a pole position (latitude 54° N, longitude 79° W), in Hudson Bay is also suggested by the Bechuanaland (Kgomodia Tshaba) samples.

A few of the Jurassic sandstones and intercalated marine horizons of Yorkshire appeared to be stable, and the relevant statistics were calculated (see the table). However, a second remeasurement after about eighteen months giving results differing slightly from the original readings, suggests instability. More reliable are probably those reversed specimens of limestones and a single sandstone sample from Scotland (fig. 4).

Fig. 4



Direction of magnetization of Jurassic rocks from Skye, Sutherland and Yorkshire.

1, 2, Lias limestones, Skye; 3, 4, 5, Gt. Estuarine Series, Skye; 6, Brorabrensceans Series, Sandstone, Sutherland; 7, 8, 9, 10, 11, 12, Estuarine Series, Sandstone, Yorkhire.

The reversed specimens were from three horizons, of which the Lower Lias represented by a single reversed sample is not significant. The other samples were from upper Middle Oolite and low in the Great Estuarine series, and these do suggest a field reversal above the horizons of the Yorkshire rocks, unless the same reversal mechanism can be applied to both limestones and sandstone.

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The Sampling of Rocks for Palaeomagnetic Comparisons between the Continents

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§ 1. Introduction

The palaeomagnetic survey in the various continents has as its objective the determination of the positions and orientations of the continental masses relative to the pole for each of the geological periods and, if necessary, for subdivisions of them. The pole to which we refer is the magnetic pole averaged over times long compared to the time scale of the secular variation, with a sample of which we are familiar from geomagnetic measurements in historic times. It is thought that this pole coincides with the pole of rotation which, when allowance is made for the effects of precession and nutation, remains fixed in space. The determination of the ancient geomagnetic declination and inclination respectively fix the orientation and the latitude of the area, from which the rocks are collected, for that geological time. The method leaves the longitude undetermined but this can be found within limits by other considerations.

Creer *et al.* (1954, 1957) have interpreted the path traced by the mean magnetic poles over the earth's crust as a movement also of the axis of rotation with respect to the land masses. They show that over geological time this motion is of roughly constant speed. It thus possesses some of the characteristics of a random walk on a sphere, and it may well be that the polar motion consists of a large number of small displacements of random direction arising from motions or displacements of matter within the earth, distributed randomly over the earth. Irving (1956) and Runcorn (1956 b) also show that there is a systematic discrepancy between the pole positions inferred from British and American rocks from the Pre-Cambrian to the Triassic and that there are reasonable grounds to interpret this as a continental displacement of 24° in post-Triassic times.

The fact that the pole positions, averaged over each period, form an orderly sequence over the surface of the earth through geological time is a strong argument that the magnetizations were acquired from the field at the time of formation and have been substantially stable since.

The carrying through of such a palaeomagnetic survey for any area of the globe involves a sampling procedure of the rock series present. It is necessary to select lithologies which faithfully record the ancient field. It is also necessary to determine how many samples are needed to obtain a satisfactory path of the polar movement for that continent.

§ 2. Sampling Procedure of Different Observers

In the summer of 1951, E. Irving and S. K. Runcorn made the first collection of sediments for palaeomagnetic work in Great Britain, which was later greatly extended by Irving. They collected red sandstones of the Torridonian series in Scotland, white and grey flagstones of Devonian age on the east coast of Scotland and the black well-bedded Silurian mudstones of the Lake District. They found that the red sandstones alone had strong permanent magnetization, a reasonably strong tendency for the directions of magnetization to be grouped together and gave good sinusoidal deflection—azimuth curves with the astatic magnetometer (see Collinson *et al.* 1957). Since this demonstration of the efficacy of red sandstones for palaeomagnetic work many other such beds have been studied : New Red Sandstones of England (Clegg *et al.* 1954), the red sandstones of Cambrian age, the Old Red sandstones of the Anglo-Welsh cuvette and the New Red Sandstones near Sidmouth (Creer 1957), the Pre-Cambrian, Carboniferous, Permian, Triassic and Cretaceous red sandstones of Arizona (Runcorn 1955, 1956 a, Doell 1955, Graham 1955). Creer found on the other hand the Jurassic clays and limestones of England unsatisfactory and Doell found the limestones and coarse sandstones exposed in the Grand Canyon had magnetizations which were weak, greatly scattered in direction and possibly unstable (private communications). Thus of sedimentary rocks only red sandstones appear to be, in general, magnetically stable and to have sufficient intensity of magnetization to be easily measured with present instruments.

The number of rock samples collected by the various observers from these various rock series differs very widely, but it is the contention of this paper that, in fact, the results are comparable for this one purpose of obtaining a mean direction of magnetization and hence a pole position for that geological period. Over 700 samples were collected from the Torridonian series, but this was done to investigate also the frequency of reversals of direction of magnetization in the series, to obtain measures of the range of the geomagnetic secular variation and to determine whether the scatter of magnetic directions correlates with the lithological characteristics of the rock, the results of which have been published (Irving and Runcorn 1957, Irving 1957).

The application of statistical methods to rock magnetism has been discussed comprehensively by Fisher (1953) and by Irving and Watson (1957). Methods for reducing the angles of confidence of measurements calculated by different observers to a comparable basis have been given by Runcorn (1957).

§ 3. APPROXIMATE STATISTICAL FORMULAE FOR DISPERSION OF DIRECTIONS OF MAGNETIZATION

The directions of magnetization of random samples of similar lithology from one rock formation will be scattered about a mean direction **F**, the relative frequency of directions at an angle θ with this being exp $(\kappa \cos \theta)$ where κ is the precision. If the rock series covers a large area it is supposed that the directions are corrected to eliminate the effect of the dipole field gradient. 63% of these directions will make an angle with the mean direction less than ψ_0, the angular standard deviation, given approximately by

$$\psi_0=81/\sqrt{\kappa} \text{ (in degrees).} \qquad (1)$$

The determination of the mean direction of the field during the time covered by the magnetization of the particular rock series is based on specimens scattered widely through the section but necessarily small in number. The angle between the true mean direction and the one calculated on the basis of these N specimens will be greater than α with probability P where

$$1-\cos\alpha=\frac{-\log_e P}{\kappa N}.$$

We will take, as is convenient, $P=0{\cdot}05$, thus we obtain a cone of confidence, or on unit sphere, a circle of confidence, the angular radius α in degrees being given by

$$\alpha=140/\sqrt{\kappa N} \qquad (2)$$

or

$$\alpha=1{\cdot}7\psi_0/\sqrt{N}. \qquad (3)$$

Thus if κ is of the order of a hundred, α is reduced to about five degrees by a score or so of specimens. In the present discussion of continental drift and polar wandering the reduction of α below this is unimportant. However groups of samples collected in different ways through a rock formation may give different mean directions **F**. Very many specimens can be collected without obtaining a true mean direction of magnetization for the geological period considered, if an unsuitable pattern of sampling is followed.

§ 4. THE CAUSES OF SCATTER OF DIRECTIONS OF MAGNETIZATION IN SEDIMENTARY ROCKS

The statistical problem of sampling a rock formation for palaeomagnetism can be put as follows. The rock formation represents a certain span of a geological period. The time represented is not necessarily the same at different localities: the 'time lines' in a rock formation may intersect the stratigraphical horizons, in other words the sediment may be diachronous. In exceptional areas such as the canyons and deserts of Arizona, rock formations are exposed through their whole stratigraphical thickness in many localities, in other areas for example in Great Britain, the exposures of a rock formation are limited in area and in stratigraphical thickness. The scatter in the direction of the magnetization of the specimens can be ascribed to the following four causes:

(1) *Imperfection of Experimental techniques.*

Errors in collection and measurement will give rise to a scatter of precision κ_1.

(2) *Failure of the rocks to become magnetized exactly along the field direction.*

Few rock series are lithologically homogenous and the sampling should be carried through in one or more of certain lithological types, each of which is analysed separately. When this is done it is reasonable to suppose that the magnetizations acquired during the deposition of the rock, or during chemical changes occurring soon after the sediment is deposited, are scattered about the direction of the geomagnetic field with a fixed precision κ_2, assuming such changes of the *intensity* of the field as seem likely to have occurred are not an important factor in determining the scatter. It would be unlikely that the precision would be independent of grain size or other lithological characteristics of the rock, which are indicative of the environmental conditions. Indeed Irving and Runcorn (1957) have shown that these are important factors in the quantitative study of the magnetization of the Torridonian sandstones of N.W. Scotland.

Two other sources of scatter arise because the geomagnetic field varies with time (reversal of polarity of the field will not be discussed in this context as it does not alter the axis of magnetization).

(3) *Deviation of the geomagnetic field from an axial dipole field.*

The geomagnetic secular variation causes variation of the direction and intensity of the field with periods spread over hundreds and thousands of years—very short on the geological time scale. The mean field is thought to be symmetrical about the axis of rotation on both experimental (Hospers 1955) and theoretical grounds (Creer *et al.* 1957).

If effect (3) only was present the direction of magnetization of specimens would be scattered with a certain precision κ_3, which would be greater the longer the time represented by the thickness of the specimens. The rate of accumulation of the red sandstones, with which we are largely concerned, is difficult to determine even in the most approximate way. However a general observation may be made. Lacustrine, deltaic and marine sediments deposited off-shore of a transgressing sea cannot represent a uniform deposition in either space or time. At any one time the sand will be deposited in areas small compared to the total extent of that formation. Strictly contemporaneous beds must therefore gradually wedge out when traced laterally. At the same time in other areas there will either be no deposition or erosion, the only record of which is the presence of bedding planes and local disconformities in the rocks today. Thus the time given by the rate of the permanent deposition divided into the thickness of the series will be less by a large factor than the time which elapsed between the earliest and latest deposition. A geological period is of the order of tens of millions of years and the thicknesses of sandstone which may represent this time are of the order of thousands of feet. Thus although the overall rate of deposition is therefore of the order of 1 inch in 1000 years, the actual time represented by the specimens measured in palaeomagnetic work, discs a few millimetres thick, may be much less than the time in which geomagnetic secular variation of a few degrees occurs, i.e. a few decades.

It seems probable therefore that the scatter of directions of magnetization of rock specimens from one site is in part due to the geomagnetic secular variation. The discussion so far has tacitly assumed that the sediments become permanently magnetized at the instant of deposition : in fact they may become so only later when due to the pressure from overlying sediments the porosity and the water content are so reduced that the magnetized particles are no longer free to turn or because the magnetization is not due to the orientation of particles already magnetized but mainly occurs during chemical changes, probably the formation of haematite layers on the quartz grains. These processes would not occur usually underneath thick layers of sedimentary material : thus the statement above that on the average the magnetization of a rock disc would occur originally within a few years still stands.

(4) *Movement of the pole of rotation with respect to the site position during the time represented by the rock formation.*

The mean rate of polar motion through the geological column found by Creer *et al.* (1954, 1957) is about 0·3 degrees per million years. Its velocity at any one time may be very much greater because there may be a random motion about the mean path or because the pole may move in jumps rather than smoothly. Examination of the present day variation of latitude data shows the polar motion at the present time could not be greater than about a few feet a year, or about 10 degrees in a million years. Thus if effect (4) was present the directions of magnetization of rock samples taken throughout the rock series could be appreciably scattered (with a precision κ_4).

§ 5. SCATTER OF DIRECTIONS OF MAGNETIZATION IN DIFFERENT SAMPLING PATTERNS

If therefore disc specimens are taken randomly through the full stratigraphical thickness of a rock formation, but selected from one lithology, their directions of magnetization will be scattered with a precision κ_r, which, if the scatter is not too large, is given by

$$1/\kappa_r = 1/\kappa_1 + 1/\kappa_2 + 1/\kappa_3 + 1/\kappa_4. \qquad (4)$$

The vector mean $\mathbf{F}_r$ of the directions, the declination of which is D_r and the inclination I_r will thus enable an estimate of the mean position of the pole for the geological time represented by the rock formation to be made.

This value of the mean is the only true estimate of the mean direction of the field during the geological time represented by the formation.

Other values of the precision and the mean direction are obtained if all the palaeomagnetic measurements made in a survey of a rock formation are given equal weight and are not selected in the above way.

If the rock samples are taken from one site where perhaps tens of feet of rock are exposed, which is a sufficient thickness of the formation for it to span a comparable fraction of the overall time represented by the formation, i.e. tens to hundreds of thousands of years, the mean direction $\mathbf{F}_s$ with declination D_s and inclination I_s of the magnetization of N_s disc specimens will be an estimate of the field, presumably smoothed of the secular variation, but which gives a position of the pole of rotation which may not be the same, because of effect (4), as that for the whole epoch represented by the rock formation. The scatter will correspond to a value of the precision κ_s given by

$$1/\kappa_s = 1/\kappa_1 + 1/\kappa_2 + 1/\kappa_3. \qquad \ldots \ldots \quad (5)$$

Both for measurements on specimens spanning a whole rock formation and on those from one site, angles of confidence α_r and α_s respectively can be calculated (and the ovals of confidence of the corresponding pole positions). α_s will be less than α_r but will not be a true estimate of the error of the field direction for that geological period.

Runcorn (1957) shows that if at each site N_s specimens are taken and their mean direction $\mathbf{F}_s$ calculated, then the mean directions will be scattered about a mean direction $\mathbf{F}_m$ with precision $N_s\kappa_s$ if effect (4) is absent. In general they will be scattered with precision κ_m given by

$$1/\kappa_m = 1/\kappa_4 + 1/N_s\kappa_s. \qquad \ldots \ldots \quad (6)$$

He also showed that F_m will be the same as F_r.

§ 6. The Significance of Mean Directions of Magnetization of Various Sedimentary Formations

Let us consider as examples measurements made on the Triassic sandstones of Great Britain and red beds of Pre-Cambrian and Permian age in Arizona. Clegg *et al.* (1954) took 43 samples from 9 sites in the Keuper Marl series, each site spanning not more than 10 feet of a succession up to 3000 feet thick. Measurement of the direction of magnetization of 540 disc specimens cut from these samples was made, an average of 60 per site. The mean direction at each site was calculated, the angle of confidence α_s of this direction ranged between 3° and 6° at the different sites. From eqn. (2) we find that κ_s is about 20.

If the mean directions of magnetization at each site are analysed, they are found to be scattered with a precision $\kappa_m = 18$. From eqn. (6) we see that if one disc specimen had been taken from each site instead of 60, κ_m would only have been halved and the value of the corresponding angle of confidence only increased by 30%.

The measurement by Runcorn (1956 a) of the mean palaeomagnetic direction of the Hakatai Shale of the Grand Canyon in which 16 samples, from which 56 discs were cut, taken at roughly equal intervals over the whole thickness of the series, i.e. 1000 feet, the angle of confidence working out as 5·4°, is a comparable result. Similarly the mean palaeomagnetic direction of the Supai Shales obtained from measurements of samples distributed through 1500 feet of section in the Grand Canyon give a κ of 15·7 and a cone of confidence of 8°, even including certain specimens which are partially unstable and which quite properly could have been rejected.

The sites at which the Triassic sandstones of England were sampled are spread over about 100 miles so that, although each site represents a very small thickness of the formation, it may be assumed that the averaging out of effect (4) was satisfactorily accomplished. The strata of the Grand Canyon was sampled at only one place but the sampling spanned the entire thickness so that it was also fully effective for the purpose of averaging out effect (4). Another example is the agreement between the positions of the Carboniferous pole (49° N, 120° E) determined by Runcorn (1955, 1956 a) from the Naco Sandstone in Arizona and that (39° N, 124° E) determined by Martinez and Howell (1956) from calcareous concretions occurring in the Barnett Shale in Texas, the mean of their measurements on six concretions from widely spaced horizons being taken.

§ 7. SYSTEMATIC ERRORS IN THE DIRECTION OF MAGNETIZATION

So far we have assumed that the directions of magnetization are without systematic bias. Various possible causes by which this could be brought about have been suggested but only one has been shown to be widespread—the tendency of the magnetization vectors of samples with different proportions of a magnetically unstable mineral phase to be distributed in a plane between the original direction of magnetization and the mean direction of the earth's field in recent times. Runcorn (1956 b) has shown that the *longitudes* of the pole positions, calculated from the mean of a number of rock specimens in which this effect is important, are not systematically in error. In general, however, the presence of a possible source of bias in the results can only be detected by the comparison of the mean directions of different rock series of similar age.

§ 8. THE SCATTER OF DIRECTIONS OF MAGNETIZATION IN LAVAS

In the sampling of lavas the cause of the scatter in the magnetization directions can be treated under the same four headings. In a single flow, however, we know that the field has not changed appreciably during the magnetization of the lava on cooling, although the strong magnetization of the surrounding lavas may cause the field in which the lava is cooling to be non-uniform. This for the formula (5) applies to a collection from one site, in which it will be possible to sample a few lavas. These will be likely to span a time of the order of the secular variation time scale.

As an illustration of the principles given above, let us consider the recent work on the Deccan Traps in India. In 1953 Irving (1954, 1956) measured the magnetization of seven samples of the Deccan Traps taken from seven localities extending over 200 miles. In a programme begun in 1954 Clegg *et al.* (1956) collected 450 samples from two sites about 500 miles apart. In the Linga area they use measurements from four flows, from each of which about 50 disc specimens were cut. For these 200 measurements α is given as 2°, therefore eqn. (2) gives $\kappa=25$. In the Khandala area a possible 20 flows were sampled, from each of which about 12 disc specimens were cut. For these 240 measurements α is given as 3°, thus $\kappa=9{\cdot}2$.

It has been shown by Runcorn (1957) that the value of $1/\kappa$ determined by this procedure is an estimate of $(1/\kappa_3+1/\kappa_4)$ and is little related to the scatter of the directions within one lava flow. Thus a more realistic value of α for the measurements of Clegg *et al.* is obtained, by using the number of flows rather than the number of disc specimens in eqn. (2). Thus for the Linga area α becomes 14° and for the Khandala area 12°. For his measurements at seven sites, Irving finds α to be 10°. It is therefore not surprising that they get similar results as shown in the table. The determination of the mean direction of magnetization of the Deccan traps by Clegg *et al.* (1956) therefore confirms Irving's result but does not add to the accuracy.

Directions of Magnetization and Pole Positions for Deccan Traps

Observer	*D*	*I*	Pole position
Irving (1956)	S 31° E	+56°	28° N, 78° W
Clegg *et al.* (1956)	S 25° E	+58°	28° N, 85° W

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Comparison of Palaeomagnetic Results for Selected Rocks of Great Britain and North America

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Recently it has been possible to compare palaeomagnetic measurements from rocks on either side of the North Atlantic and from such comparisons to deduce that relative movements between North America and Europe have taken place. This paper proposes to describe briefly three periods of geologic time from which sufficient palaeomagnetic evidence has been collected to warrant making certain conclusions. These three periods are late Pre-Cambrian, Permian and Upper Triassic.

The author has measured an extensive suite of Keweenawan rocks (Pre-Cambrian) which were collected from around Lake Superior. The sub-divisions of the Keweenawan, from which samples were measured, are Portage Lake, Copper Harbour, Freda and Nonesuch, Jacobsville and Chequamegon. The Portage Lake, which has been generally classified as Middle Keweenawan, consists of an enormous thickness of lava flows, principally basalt and andesite, which are interbedded with some thin layers of conglomerate and sandstone. The Copper Harbour, which is considered as Upper Keweenawan, as are all the rest of the above mentioned formations, is mainly a very coarse conglomerate, consisting principally of boulders of rhyolite and other more acidic rocks in a sandy matrix. A subordinate amount of the boulders are basalt and andesite, identical with the underlying lavas. There are some lenses of medium to coarse grained reddish sandstone interbedded with the conglomerate. Furthermore, there are some basaltic and andesitic lavas in the Copper Harbour. There is a sharp lithological break at the top of the Copper Harbour, where coarse conglomerates pass up into fine grained sandstone, siltstone and shale within a few feet. This sandstone and shale is the Nonesuch, which, with the overlying Freda, consists of fine grained reddish or purplish grey sandstone, siltstone and shale. The Jacobsville is mainly a fine to medium grained sandstone, brick red in colour except for many white spots where evidently reduction of red haematite has taken place. The Chequamegon is a medium to coarse grained sandstone, which is the stratigraphically highest Keweenawan formation to be found. The palaeomagnetic results for these formations are plotted on a stereographic polar projection in figs. 1–5. The conventional notation, except where stated otherwise, is that full circles are north poles on the lower hemisphere and open circles are north poles on the upper hemisphere.

The magnetic stability of these rocks may be shown in a number of ways. The fact that except for the Chequamegon the remanent directions of magnetization are quite far from the present field is in itself a good indication of fairly strong stability. Pebbles of basaltic and andesitic lava were collected from the Copper Harbour. Their measured directions are plotted in fig. 6. The randomness of this plot indicates that the lavas have been magnetically stable since Copper Harbour time. In the Freda and Nonesuch it is possible to find rocks some of which are flat lying and others practically vertical. Some of these rocks are plotted in figs. 7(*a*) and 7(*b*) to show their remanent direction without, and with, correction for geologic dip. The crosses on fig. 7(*a*) are the bedding poles plotted on the upper hemisphere. Thermal decay curves have been obtained for selected rocks from the Keweenawan, and they all exhibit a thermal decay similar to that of thermo-remanent magnetization with no change in the direction of the vector.

Samples of Permian rocks have been collected from the Mauchline basin of Scotland. In this locality are found 500 ft of olivine-basalt lava overlain by approximately 2000 ft of red and orange desert sandstone. Samples of both lithologies have been measured and are plotted in figs. 8(*a*) and 8(*b*). Although the sediments are more scattered it can be seen at a glance that they give a result quite consistent with the lavas.

Formation	Declination *D*	Dip *I*	No. of Specimens *N*	α†	Pole position	
Portage Lake	282° E	+41°	31	4°	170° W	25° N
Copper Harbour	294° E	+32°	25	7°	176° E	30° N
Freda and Nonesuch	285° E	− 1°	68	3°	169° E	9° N
Jacobsville	250° E	−11°	15	13°	170° W	14° S
Chequamegon	30° E	+74°	15	6°	133° E	69° S
Mauchline lavas	180° E	− 4°	34	8°	175° E	36° N
Mauchline sandstones	187° E	− 6°	26	12°	163° E	37° N
Triassic	12° E	+14°	32	3°	91° E	41° N

† Radius of 95% circle of confidence calculated by Fisher's Method (1953).

Finally samples of Triassic rocks from the Connecticut Valley in the State of Connecticut were collected and measured in order to compare the Triassic of America with the Triassic of Great Britain, which has been so extensively measured by Clegg *et al.* (1954). These results are plotted in fig. 9. The fact that there is a reversed group would indicate that these rocks do not have very much isothermal remanent magnetization superimposed on them and are therefore stable.

It is possible to compute for each mean direction of magnetization found in the above mentioned rocks a corresponding position of the magnetic pole. This computation assumes that secular variation and random errors will be eliminated in the process of meaning and that the earth's magnetic field is essentially a dipole. In the table the mean directions, the number of samples, the 95% circle of confidence and the mean pole positions, are listed.

These pole positions and those found by other workers have been plotted for late Pre-Cambrian time in figs. 10(*a*) and 10(*b*). In fig. 10(*a*) the European and North American continents are assumed to have been in the same relative positions in the late Pre-Cambrian as they are today. The pole positions are marked by letters ; A for the Adirondack results of Buddington and Balsley (1954) ; G for dykes from Michigan measured by Graham (1953) ; H for the Hakatai shale measured by Runcorn (1956) ; P for the Portage Lake ; C for the Copper Harbour ; F for the Freda and Nonesuch ; J for the Jacobsville ; B for the Chequamegon ; D and T for the lower and upper Torridonian of Scotland measured by Creer *et al.* (1954). Figure 10(*b*) shows the relative positions of the poles if it is assumed that America has moved 45° westward in longitude from Europe since the late Pre-Cambrian. This shows that the results from Europe and North America agree much more closely if one assumes that such a shift has taken place.

In figs. 11(*a*) and 11(*b*) the same kind of plotting of pole positions for Permian time has been done. In fig. 10(*a*) no continental drift has been considered while in fig. 10(*b*) a 45° drift westwards in longitude of America from Europe is postulated. Once again the results are much more in accordance with the idea that continental drift of such a magnitude has taken place since Permian times. The various pole positions are marked as follows :—

L for Mauchline lavas ; S for Mauchline sandstones ; E for the Exeter Traps measured by Creer *et al.* (1954) ; R for the Supai of southwestern America measured by Runcorn (1956) ; D for the Supai measured by Doell (1955) ; G for the Supai measured by Graham (1955).

The pole positions for Triassic time are plotted in figs. 12(*a*) and 12(*b*). The pole marked C is that of the Connecticut Triassic while that marked T is the pole found by Clegg *et al.* (1954). The same relative shift of America with respect to Europe of 45° west in longitude brings the results in good agreement.

These results indicate that America may well have drifted westwards from Europe by the rather large amount of 45° since Triassic times. This is in good agreement with the suggestions which were made by Alfred Wegener at the beginning of this century and which have been, up to now, viewed with great scepticism by most geologists.

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Fig. 1

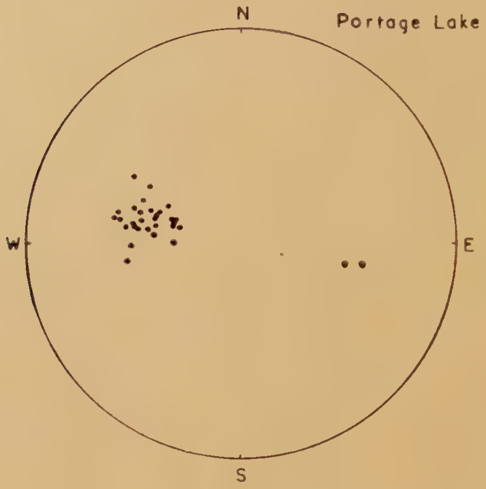


Fig. 2

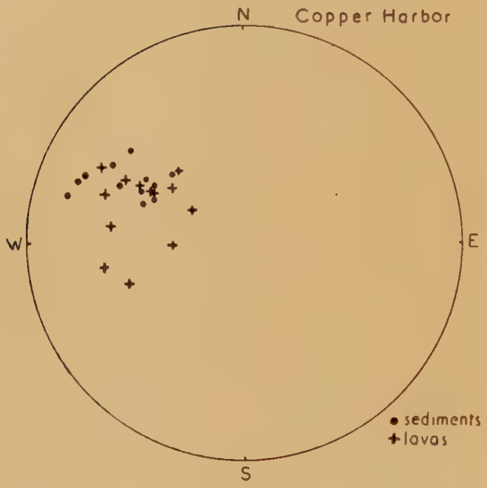
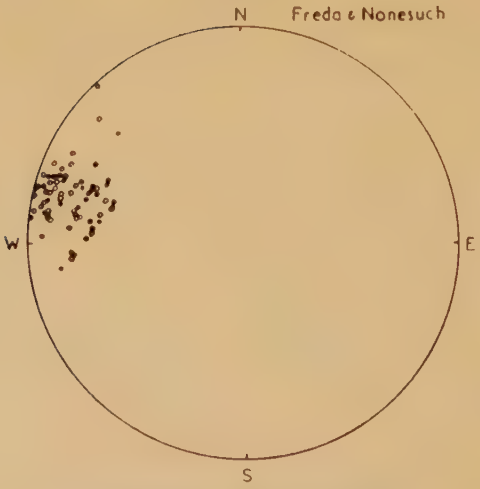


Fig. 3



Stereographic Polar Projections.

Fig. 4

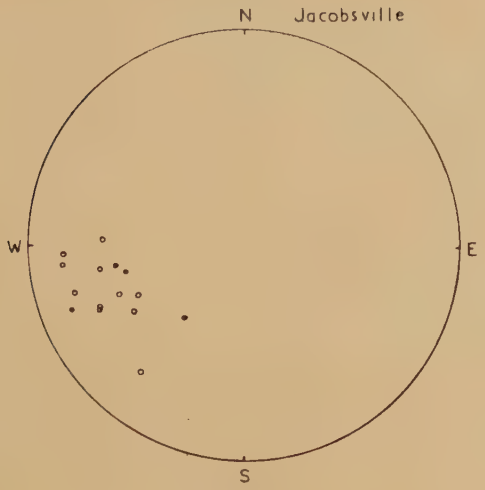


Fig. 5

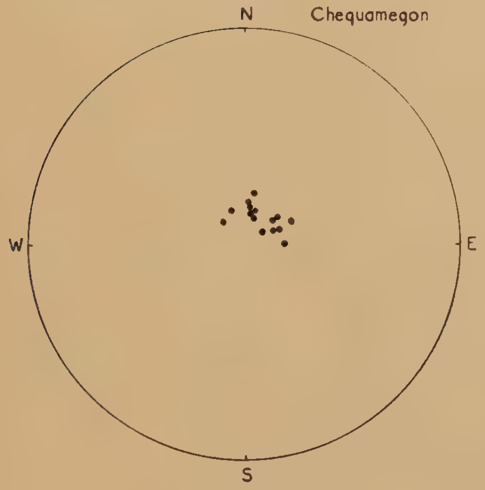
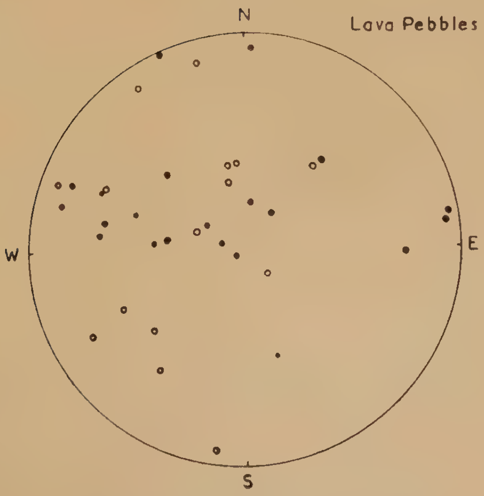
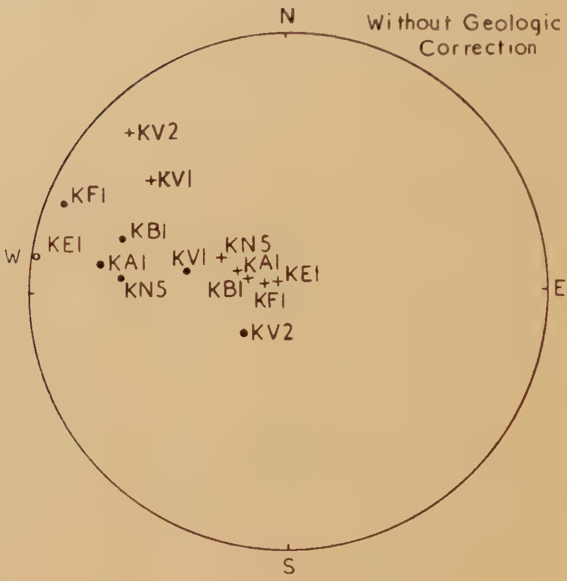


Fig. 6



Stereographic Polar Projections.

Fig. 7(*a*)



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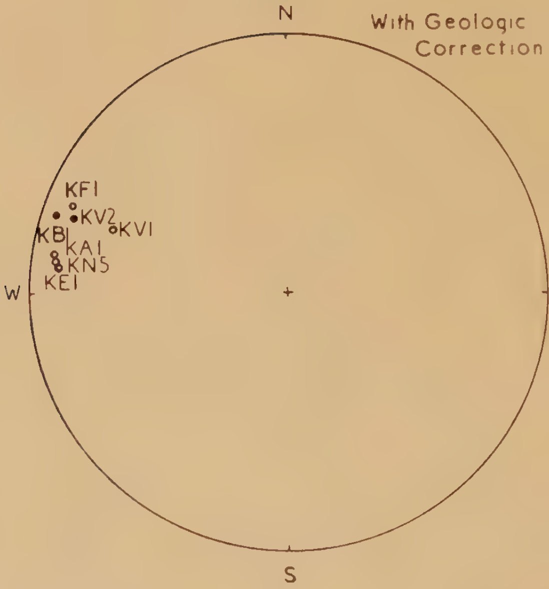

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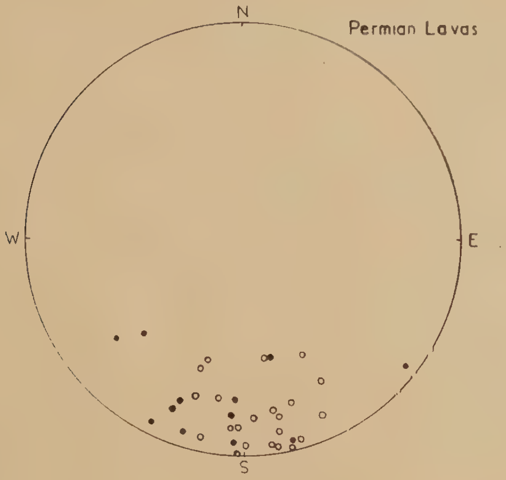

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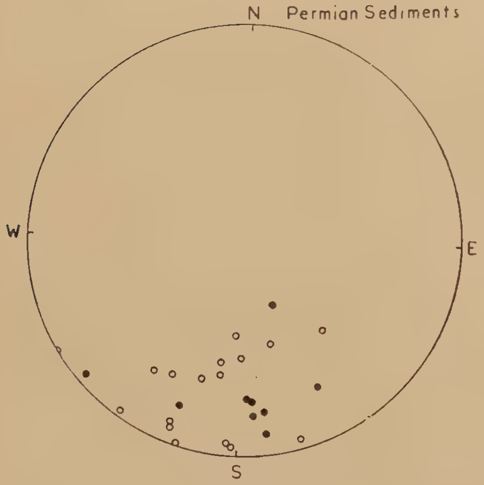
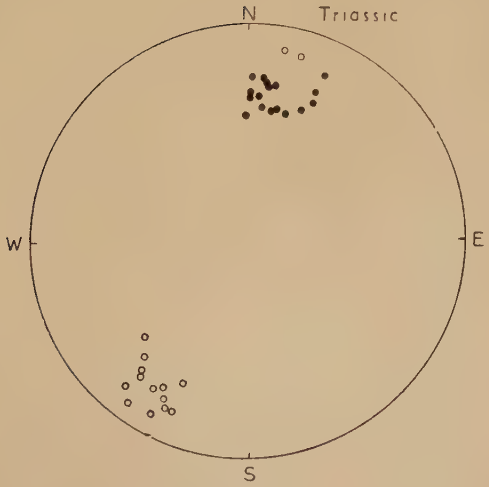


Fig. 9



Stereographic Polar Projections.

Fig. 10(*a*)

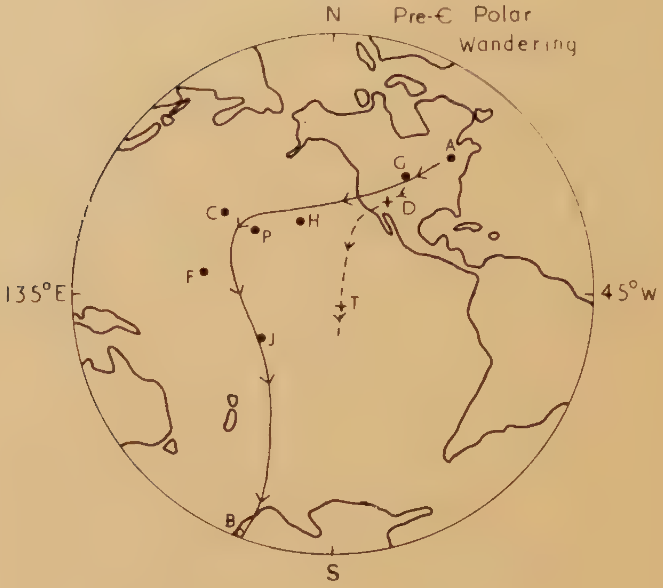


Fig. 10(*b*)

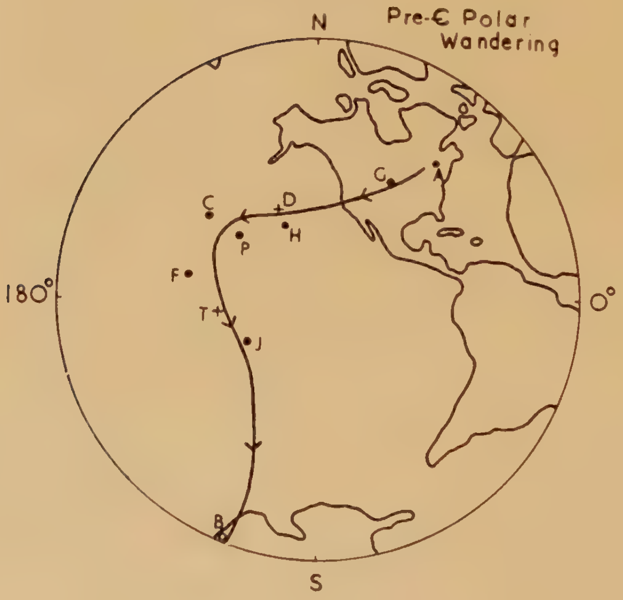


Fig. 11(*a*)

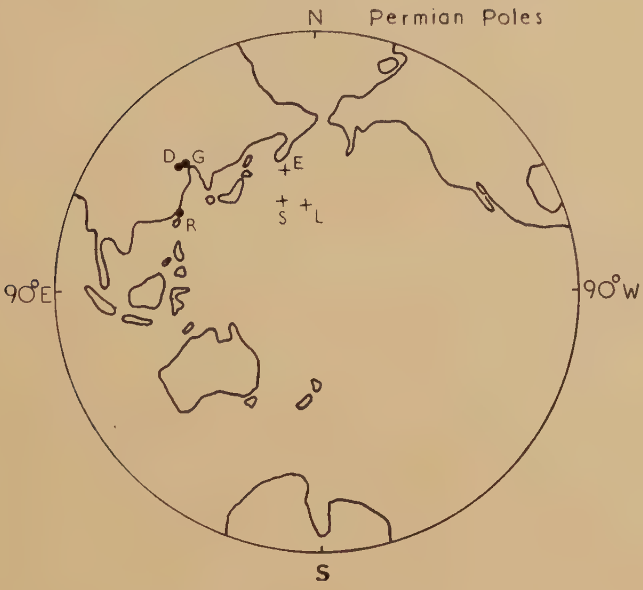


Fig. 11(*b*)

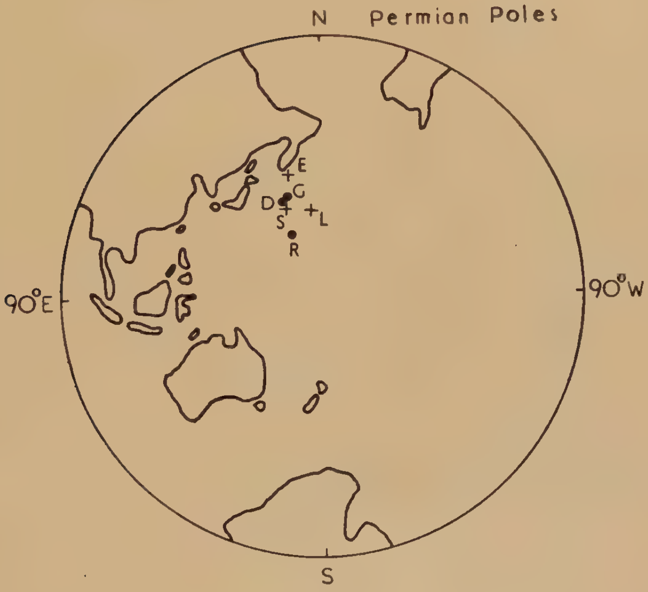


Fig. 12(*a*)

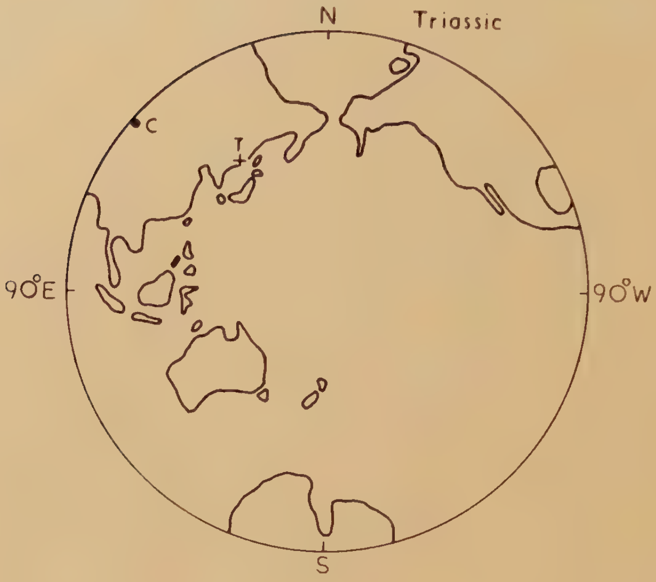
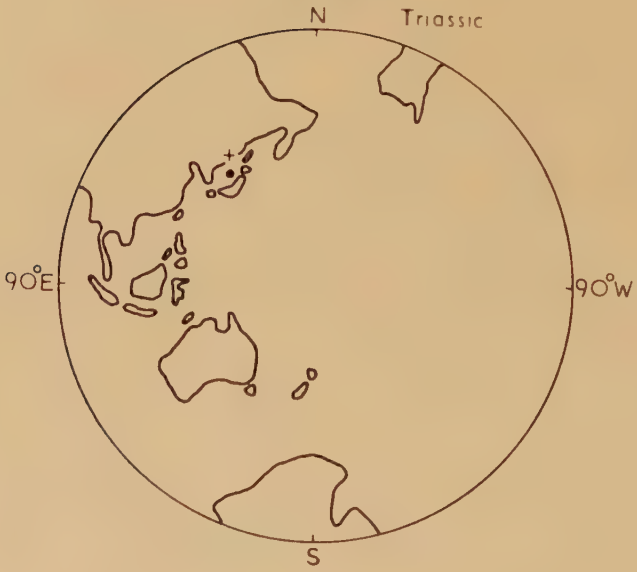


Fig. 12(*b*)



Palaeomagnetic Investigations of Carboniferous Rocks in England and Wales

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Studies of the remanent magnetization in Carboniferous sediments began early in 1954. At that time in Cambridge, Irving (1954) had shown that the Torridonian sandstones of Scotland exhibited repeated reversals of the remanent magnetic vector's direction, but Creer (1955) was finding such reversals infrequent in the Lower Palaeozoic sedimentary rocks of England. Clegg *et al.* (1954) were completing a study of Triassic sedimentary rocks which showed magnetic directions at variance with the present geomagnetic field. It seemed apparent that the study of remanent magnetization in one Palaeozoic system in detail was needed. I will summarize the results of that investigation so far completed in England and Wales.

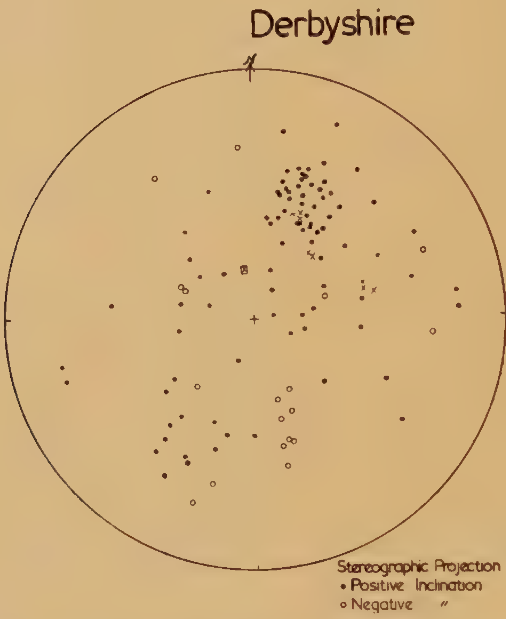
The Carboniferous system commended itself for this study for several reasons. The economic exploitation of units in it has resulted in detailed knowledge of its stratigraphy and structure. This portion of geological time included periods of considerable stability in earth conditions. The coal frequently occurring with the sedimentary rocks to be investigated would provide good indication of metamorphism. Good exposures were readily available in the United Kingdom and I was familiar with the North American section.

Coal fields lying east of the Pennines, principally in Derbyshire, were picked for the first studies. These rocks appear to have been unaffected by any major earth movements since the time of their formation. Collections were made covering the rocks from the Lower Carboniferous through the millstone grits into the lower coal measures. Fourteen sites yielded 103 measurements which I reported at the conference on Anomalous Magnetization (National Science Foundation 1954). These magnetic directions were all in the northeast quadrant and with inclinations shallower than that of the present field in this area. The mean azimuth and dip were N 27° E and 36° down but there appeared to be a progressive shallowing of the dip as one went upwards in the time sequence. This direction did not differ greatly from that reported for Triassic rocks (Clegg *et al.* 1954) but was steeper in inclination than some Permian results reported by Creer (1955).

Remeasurement of this material six months after the early work showed the directions stable for that length of time. This success influenced the decision to build from the Derbyshire rocks a ‘ type section ’ against which to compare measurements elsewhere. This was done during the following year and resulted in sampling from 34 sites (including an extensive underground section obtained in the Arkwright Colliery), yielding 142 orientated rocks and over 500 measurements. The directions of remanent magnetization in 84 of these rocks is shown on fig. 1†.

The trend established in the earlier work is apparent again, but the data much less consistent with its greatly increased scatter. There has not yet appeared any simple relationship between geographical or stratigraphical position of the collecting sites and the measured directions. Treated as a whole, the data give a much steeper dip for the mean (azimuth N 70° E, dip 83° down with a 20° radius of confidence at the 95% level) than that of the tight group appearing in the N.E. quadrant and quoted earlier. This may be due simply to the influence of a magnetically unstable component in many samples adding a direction near that of the present field to any remanent direction. Three interbedded volcanic rock units, locally referred to as toadstones, form a more consistent sub-group. They yield a mean direction of N 48° E, dip 47° down with a 13° radius of confidence at the 95% level from nine samples. This discrepancy of about 10° steeper inclination of the volcanic rocks than their associated sedimentary rocks (47° as compared with 36°) is to be noted.

Fig. 1



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† In this and the following figures a positive dip is taken to be downward.

Fig. 2

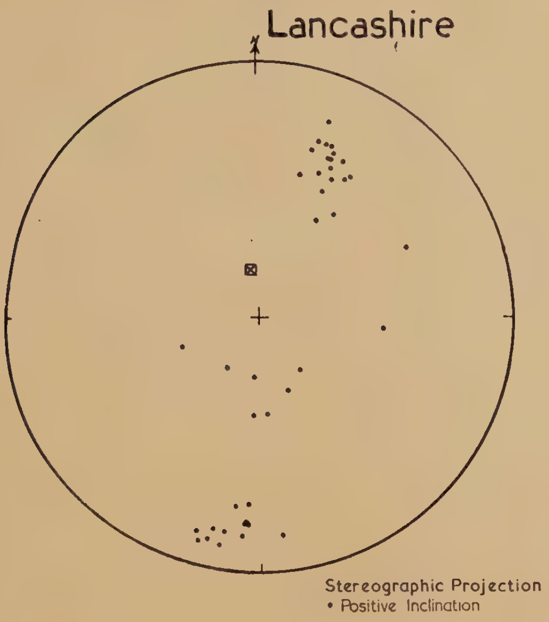
Lancashire
N
Stereographic Projection
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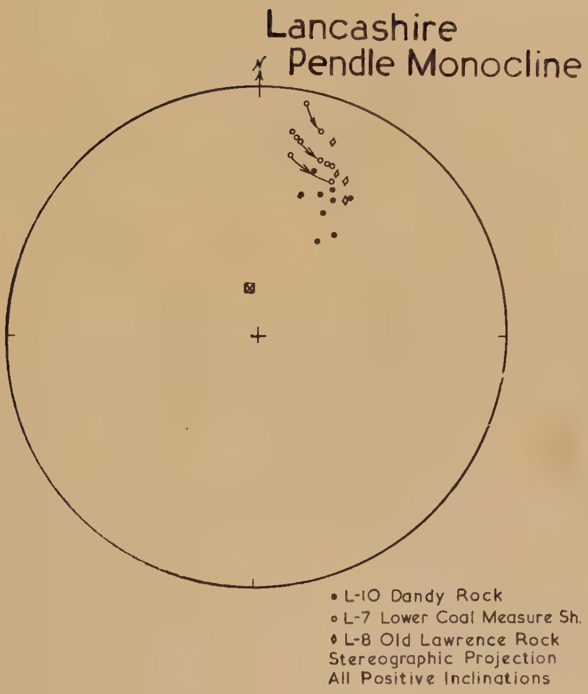
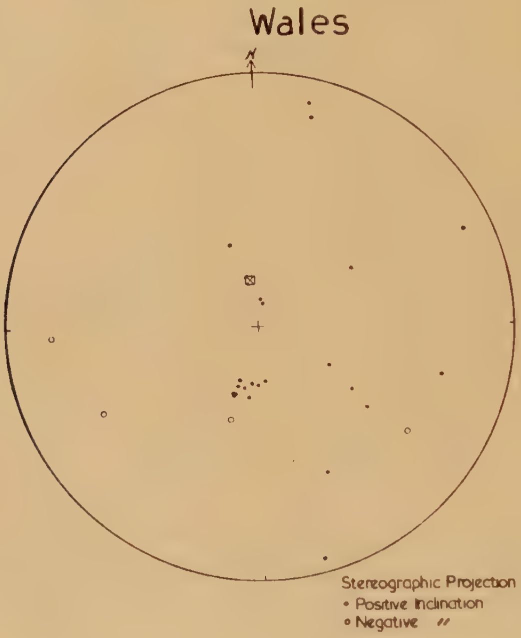
Fig. 3


Lancashire
Pendle Monocline
N
• L-10 Dandy Rock
∘ L-7 Lower Coal Measure Sh.
◊ L-8 Old Lawrence Rock
Stereographic Projection
All Positive Inclinations

Lancashire Carboniferous rocks were collected to compare with Derbyshire's. From 12 sites, 49 orientated rocks were taken and their data are shown on fig. 2. A N.E.-trending, moderately inclined group is in evidence as for Derbyshire. There is also a smaller grouping in the S.W. quadrant which comes from rocks in the Millstone Grit series.

The Pendle Hill area of Lancashire provided an opportunity for a field check of stability in the Pendle monocline. Here rocks from one site on the north limb of the fold, dipping 37° southward had their magnetic directions compared with rocks from two sites south of the fold axis where the beds are practically horizontal. All these directions, both before and after unfolding of the north limb, are shown on fig. 3. This indicates that the remanent magnetization was most likely acquired before the folding occurred in the late-Carboniferous.

Fig. 4



Results from Wales are plotted in fig. 4. There is no evident correlation between these data and that of Derbyshire and Lancashire. The yield from the first fifty rocks collected there has been disappointing and a second, larger collection has now been made but work on it is not complete.

Also collected, but not yet measured, are forty rocks from the Northumberland coalfield and ten more from Derbyshire. Additional collections are planned for coalfields in the United Kingdom and on the continent.

Lithologies dealt with in these studies have been the full range of sedimentary rocks, but with a bias in the collection towards the finer-grained clastic rocks. Most of these come from clay pits or the mudstone units of the opencast coal pits. One of the rocks strongest in magnetic intensity (10 ^{4} e.m.u./cm^{3}) was a black shale, but it was unstable and examination with a microscope suggested that pyrrohtite was the principal magnetic mineral. Some marly limestones have been measurable and this has been a very useful fact in the Yordale series. Work in the Millstone Grits, where a very wide range of grain sizes is available, supports Irving's (1954) views that silts are generally the most suitable size fraction with scatter of the magnetic measurements increasing as one goes to coarser or more poorly sorted materials.

Working with such a range of materials is disappointing in that between a third and a half of what is collected may be below the limits of measurement (about 10^{-7} e.m.u./cm^{3}) or unstable. For example, in the Pennant sandstone of Wales though the iron content is appreciable it is locked in micaceous type minerals and the magnetic moment is often undetectable.

Heating and a.c. demagnetization studies of these rock suites have but barely begun. The former have been concentrated on the igneous toadstones. They show an N.R.M. about 10% of the T.R.M. for the rocks in a field of 0·5 oe.

Studies of Carboniferous rocks in North America have been reported by Runcorn (1955) and Martinez and Howell (1956). The former's rocks are possibly later in time than any reported on here. Still, when related to a global pattern all these results would fit with a geomagnetic axis orientated with one pole slightly northwest of the main Japanese islands in Carboniferous time to an accuracy well within the range of uncertainties arising from internal consistency, age correlations and precision of measurement. More disturbing for this conclusion are the divergent results obtained from studies of igneous rocks and their associated zones of baked country rock. These will be discussed separately at this conference by C. W. F. Everitt of Imperial College (Clegg, Deutsch, Everitt and Stubbs 1957).

ACKNOWLEDGMENTS

In these studies I have received generous assistance from colleagues at Cambridge University and Imperial College, London, H.M. Geological Survey, the National Coal Board, and the Department of Scientific and Industrial Research.

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Recent Magnetic Investigations at Cambridge University

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Recent in geological time as well as in the time of investigation are our studies of archaeological materials. Working with the Museum of Classical Archaeology, our department has concentrated its attention on the baked clay walls of ancient kilns. These we can collect *in situ*. The data are yielding us a curve for the secular variation of the magnetic field in England since the beginning of the Christian era.

Allied with this work is an experiment conducted on a reconstructed kiln of the Romano-British type. This was fired in an attempt to duplicate the ancient pottery technique. We viewed it as an opportunity to test our theories on the fixing of the magnetic vector in ancient kilns. The kiln was fired last month (October 1956). We studied temperatures obtained inside the kiln and in its walls, the change in magnetic moment of the kiln and its contents during firing, and the anomaly in the geomagnetic field caused by the kiln after its use. Samples were removed from the kiln wall for study in the laboratory in the manner done for archaeological remains. These do document the magnetic field directions at the place of firing. A report of this will be published next spring.

Our investigations of the field change in the vicinity of the kiln were novel in that they made use of the proton precession technique. We hope to use such an instrument in the future for locating buried kilns.

Mr. R. Girdler has studied the palaeomagnetism of some Jurassic rocks from Dorset and Devon. Though still in progress, this work shows a mean direction further from the present magnetic field than that of Nairn's which was reported at this conference. For example, the Bridport Sands have a mean direction of N 15° E with a downward dip of 54° and the Northants Iron-stones, N 19° W with a downward dip of 56°.

Studies of the remanent magnetization in the Dartmoor Granite show a very scattered remanent magnetic direction. The intensity of magnetization is low (10^{-6} to 10^{-7} e.m.u./cm^3) and the magnetic properties of the rock are quite variable. This is a preliminary study to investigations in the metamorphosed Culm measures of Carboniferous age lying north and east of the granite.

Finally I will mention some thermal studies done on Old Red Sandstones samples. These are from the Brecon Beacons area and were studied in conjunction with Carboniferous material from the South Wales coalfield. The work was done at Imperial College with the kind consent of Professor P. M. S. Blackett on a magnetometer-furnace apparatus constructed by J. H. Leng. These Red Sandstones when cooled from above their Curie temperature in a field of 0·6 oe had a T.R.M. of the order of half their N.R.M. This contrasts sharply with the behaviour of similar material studied by Creer which had a N.R.M. a fraction of its T.R.M. This question must be posed : to what extent is this reported behaviour typical of material which may be suspected to have acquired a chemical magnetization ?

Rock Magnetism: a New Approach to Some Palaeogeographic Problems

By E. IRVING
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§ 1. INTRODUCTION

GEOLOGISTS have often attempted to elucidate the physical geography of the Earth in the past, that is the past distribution of continents and oceans, and the variations in topography and climate. However, the geological data are capable of many differing interpretations so that the conclusions of different scholars have by no means been identical. There are two issues upon which the division of opinion has been most severe. These are the questions of polar wandering and continental drift. Many geologists believe that although from time to time epeiric seas may have covered broad expanses of the land, and the creation of new mountain ranges from geosynclines may have altered the form of the continents, the deep ocean basins and the major shield areas of the Earth have remained similar in dimensions and permanent in position at least since the beginning of the Palaeozoic. Neither are there any palaeoclimatic reasons for supposing that the spin axis of the Earth has changed its position with respect to these permanent continents and oceans. The second body of opinion places a different interpretation on the palaeoclimatic data, and holds that the geographic axis of the Earth has wandered relative to the crust. Moreover the evidence of palaeontology and the configuration of the continents and their orogenic belts has lead these same people to suppose that relative movement of the continents as well as a general polar shift has occurred.

In recent years a good deal of attention has been paid to surveys of palaeomagnetic directions in rock formations of various ages. In many cases good reasons have been found for identifying these directions with the directions of the geomagnetic field at the time and place at which the rock was formed (Graham 1949, Runcorn 1955). These surveys have shed much light on the problems of polar wandering and continental drift.

It appears (for reasons given later) that the geomagnetic field when viewed from the Earth's surface over periods of time of the order of 10^3 to 10^4 years approximates to that which would be produced by a geocentric axial dipole. The irregularities due to the non-dipole components of the field have shorter periodicities and are averaged out. Thus from estimates of the mean directions of magnetization of a rock formation (Fisher 1953, Watson and Irving 1957), estimates of the pole position may be made (Creer *et al.* 1957, Irving 1956). If formations from successive geological periods are studied in the same region, movements of the pole relative to this region may be detected. In this connection four possibilities have to be considered.

A. That neither polar wandering nor continental drift has occurred. This may be termed the ' permanency ' hypothesis.

B. That the Earth's axis has wandered with respect to the crust. This is the hypothesis of polar wandering.

C. That the axis has remained fixed with respect to the crust of the Earth, but that the continents have moved relative to each other upon this crust.

D. That both polar wandering and relative continental drift have occurred. This is polar wandering and drift as envisaged by Wegener (1924) and Köppen and Wegener (1924). Hypotheses C and D are readily distinguishable in theory but it will be difficult at least for sometime to separate them strictly in the results.

This paper describes new data from Australia, and reviews results from elsewhere. These four propositions are considered in the light of this data. They will be referred to as hypotheses A, B, C and D.

Four other points need to be mentioned here. Firstly, the data is always corrected for geological tilt so that the magnetic directions are referred to the bedding plane, or, in the case of lavas to the bedding of associated sediments. The bedding is assumed horizontal at deposition. In particular cases this assumption will be in error, but the error will be lost when a large number of localities are considered.

Secondly, there is the question of reversals. It is frequently found that samples from a rock series have parallel directions of magnetization but have mixed polarity. The only importance of reversals in the present context is that they introduce an ambiguity in sign of the geocentric dipole, and in all calculations, both normal and reversed rocks will be considered together without regard to sign.

The third point concerns magnetic stability. Certain tests devised by Graham (1949) allow unstable and stable rocks to be distinguished. In practice it is impossible to perform stability tests on all rock specimens, but, by carrying out tests on rocks of different types and then confining collection to those rocks which are found to be suitable, it is possible to obtain stable magnetic directions with a high degree of certainty. In this paper only those results are considered for which high stability may be proved or reasonably inferred.

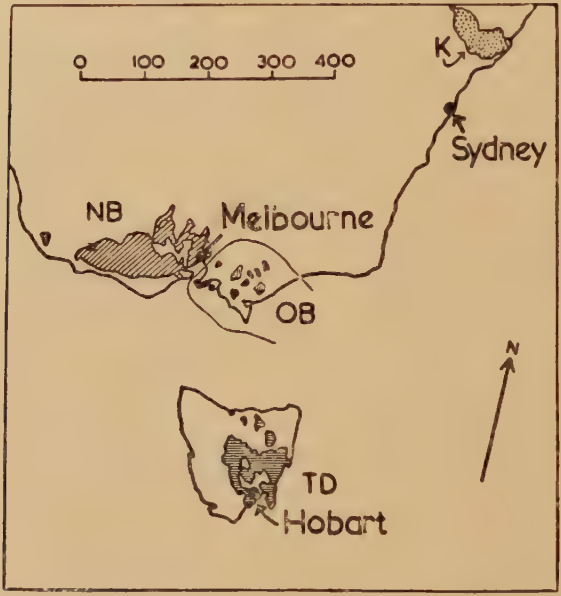
Lastly, comparisons between pole positions from rock formations in different continents are possible only when the formations are, as nearly as possible, contemporaneous. Results from rocks with very doubtful age relations are therefore not considered.

§ 2. The Position of the Pole in the Past

2.1. *Australian Results*

The youngest rocks suitable for palaeomagnetic work in Australia are the basic lavas flows of the Great Valley of Victoria which cover an area of about 10 000 square miles (fig. 1). These lavas were developed from numerous cone intrusions during the Pliocene, Pleistocene and Recent Epochs. Thirty-two localities spread over the outcrop have been studied (Green and Irving 1957), two samples being obtained at each site. The mean direction at each site are plotted in fig. 2. Sixteen sites have 'reversed' magnetization with southerly declinations and positive dip. Thirteen sites have 'normal' magnetization with northerly declinations and negative dip. Three sites have mixed polarity. This pattern of repeated reversals is similar to that found in rocks of comparable age from the northern hemisphere. The mean dip of 60° (table 1) does not differ significantly from the dip (58°) of the axial dipole field, but is less than the inclination (67°) of the present Earth's field. The average declination also conforms to the axial dipole field. The pole, with zone of error, is given in fig. 3 and coincides with the present geographic pole.

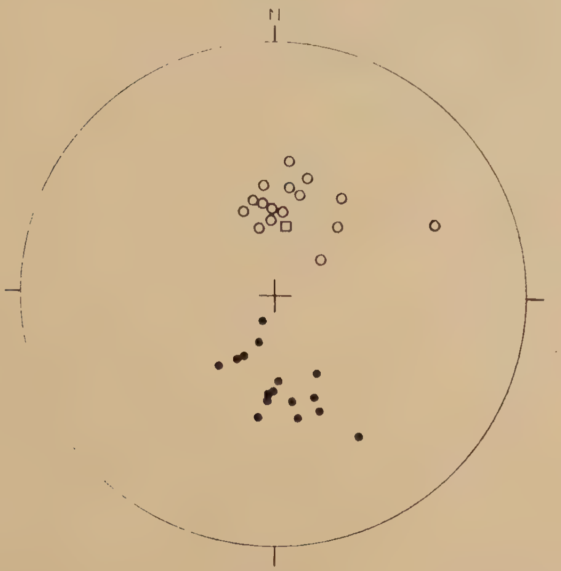
Fig. 1



A sketch-map of S.E. Australia showing the outcrop of the rock formations from which palaeomagnetic results are now available. The formations are, the Newer (NB) and Older (OB) Basalts of Victoria, the Dolerite sills (TD) of Tasmania and the Kuttung Series (K) of the Hunter Valley. The cities of Sydney, Melbourne and Hobart are marked. The scale is in miles.

The Older Basalts of Victoria are of Lower Tertiary age and are sporadically exposed over an area of approximately 5000 square miles (fig. 1). Three samples have been taken at each of fifteen sites. The mean site directions are plotted in fig. 4. The mean declination is easterly (table 1),

Fig. 2



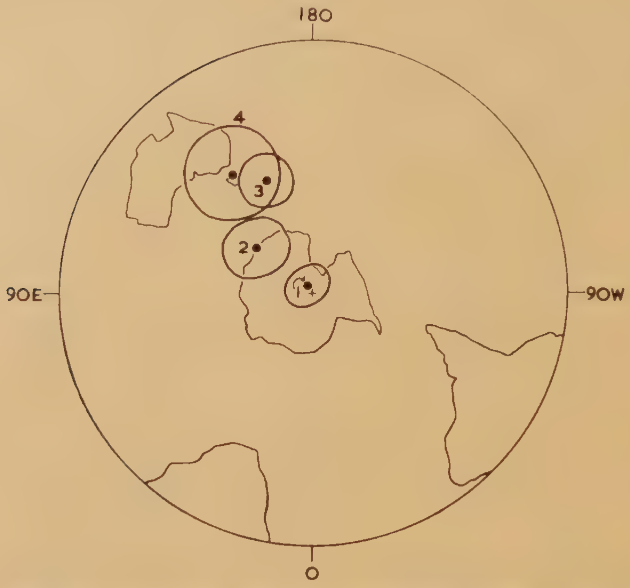
The Directions of Magnetization at 32 sites in the Newer Basalts of Victoria. The north-seeking directions are plotted as circles when they are in the upper hemisphere (that is 'normal' magnetization in the southern hemisphere) and as dots when in the lower hemisphere. The plane of the projection, which is a Schmidt equal-area net, is the present horizontal. The direction of the present Earth's field is indicated by a square.

Table 1. Pole Positions given by Australian Results

Formation	Age	Mean direction of magnetization				Sampling area		Ancient pole position			
		N	*D*	*I*	α	Lat.	Long.	Lat.	Long.	δm	δp
1. Newer Basalts of Victoria	Pliocene to Recent	32	3·4	−59·8	4·8	38S	143·5E	86·3S	102·1E	7·2	5·5
2. Older Basalts of Victoria	Eocene and Oligocene	15	17·0	−72·9	6·8	38S	145·5E	66·8S	122·7E	12·1	10·8
3. Dolerite Sills of Tasmania	Cretaceous or Jurassic, probably Jurassic	30	325	−85	3·5	42S	147E	50S	157E	7	7
4. Kuttung Lavas of the Hunter River Valley	Upper Carboniferous	5	350	−85	8	33S	151·5E	43S	154E	16	16

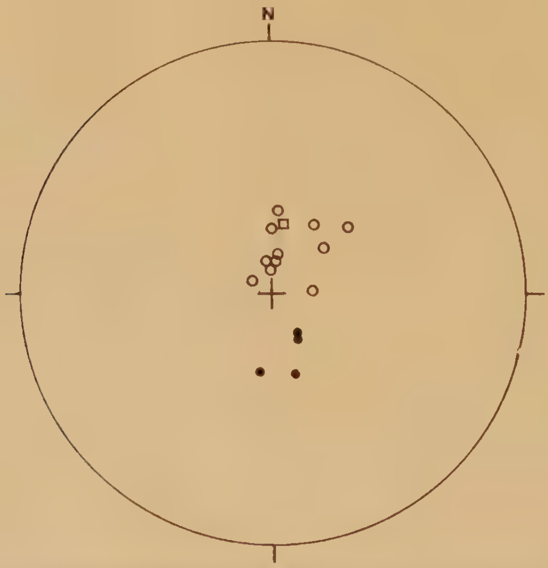
N is the number of sites from which samples have been obtained; *D* is the declination in degrees east of geographic north and *I* is magnetic inclination positive when below the horizontal, the direction being calculated without respect to sign; α is the error at $P=0{\cdot}05$ (Fisher 1953); δm and δm are the semi-axes of the oval area round the pole position at the same probability, δp is the co-latitude error and δm is the error in the perpendicular direction (see Creer *et al.* 1957 or Irving 1956 b). In this and in tables 2, 3 and 4 the numbering is consistent with that in figs. 3, 6, 7, 8, 11, 12, and 13.

Fig. 3



The Pole Positions calculated from the Australian data. The projection is Lambert's polar equal-area (Schmidt net). A zone is marked round each pole which is the area within which the pole lay at $P = 0{\cdot}05$. The poles are numbered as follows: 1, New Basalts; 2, Older Basalts; 3, Tasmanian dolerites; 4, Kuttung volcanics.

Fig. 4

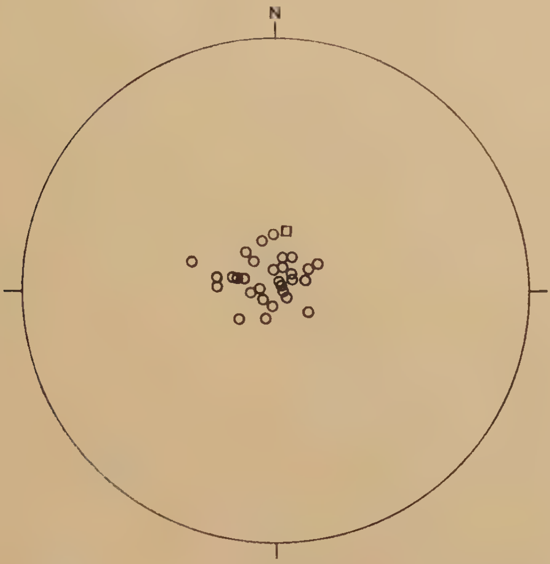


The Directions of Magnetization at 15 sites in the Older Basalts of Victoria. The conventions are as for fig. 2.

and the mean inclination of 74° is steeper than either the axial dipole field or the present Earth's field. The pole (fig. 3) is on the fringe of Antarctica.

The dolerite sills of Tasmania cover an area of about 8000 square miles (fig. 1). They were probably intruded in the Jurassic although there is some likelihood of their being Cretaceous. The directions (Irving 1956 a, at thirty sites (two samples at each) are plotted in fig. 5 and the mean direction is given in table 1. These samples have normal magnetization, but a few cases of reversed magnetization have been recorded by Jaeger and Joplin (1955). The mean dip is 85° and the pole is in the vicinity of Tasmania (fig. 3).

Fig. 5



The Directions of Magnetization at 30 sites in the Dolerite Sills of Tasmania. The conventions are as for fig. 2.

A survey of the magnetic directions in the Permian and Carboniferous rocks of New South Wales is at present being undertaken by the author. Three lava flows with stable magnetization have been located in the Kuttung Series. The inclination (table 1) is steep, and the pole is near Tasmania (fig. 3). This result has recently been confirmed by observations on the glacial varves of the Kuttung Series.

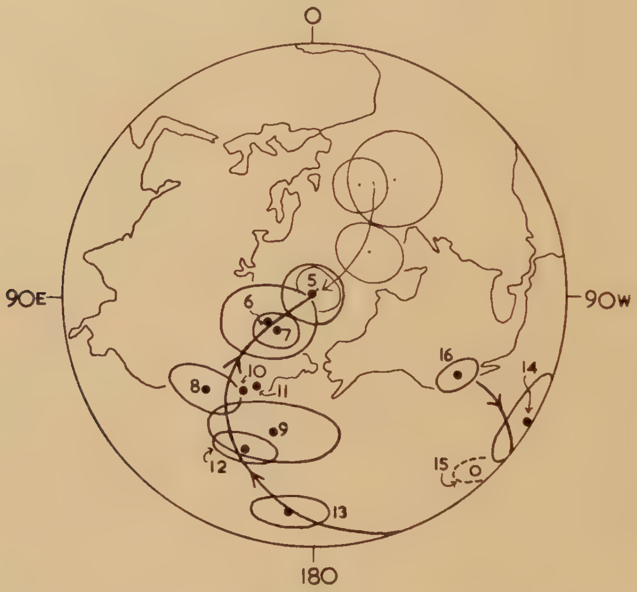
2.2. *Results from N.W. Europe*

These are summarized in table 2 and plotted in fig. 6.

The field direction in historic times (back to about 400 B.C.) has been obtained from palaeomagnetic work on the lavas of Mt. Etna in Sicily

(Chevallier 1925). The mean field direction approximates to that which would be produced by a geocentric axial dipole whose axis is along the axis of spin. Further back in time Hospers (1955) has shown that from his own data and that of Roche (1951), Bruckshaw and Robertson (1949), Bruckshaw and Vincenz (1954) and Bancroft (1951), that this result holds for Miocene, Pliocene and Pleistocene and Recent rocks of Europe and Iceland.

Fig. 6



The pole positions calculated from the European data. The projection is Lambert's polar equal-area net. The approximate path of polar movement is given in thick line. The Australian poles (the antipoles to those in fig. 3) are added in thinner line to facilitate comparison. The poles are numbered as follows: 5, Miocene of Iceland, for other Upper Tertiary and later pole determinations see Hospers (1955); 6, Oligocene; 7, Eocene; 8, Triassic; 9, Permian; 10, 11, Carboniferous; 12, Devonian; 13, Cambrian, 14, Longmyndian; 15, Upper Torridonian; 16, Lower Torridonian.

The magnetic directions in the Antrim basalts of Eocene age in Ireland (Hospers and Charlesworth 1954) and a group of Oligocene intrusives from the Auvergne (Roche 1950) give poles near the present position of the new Siberian Islands.

Clegg *et al.* (1954) have reported results from the Triassic Keuper marls and sandstones of England which give the pole position at this time as near Vladivostock.

The pole consistent with the directions of magnetization of the Permian Exeter Volcanic Series (Creer *et al.* 1957) lies in the north Pacific Ocean.

Table 2. The Pole Positions obtained from the European Results

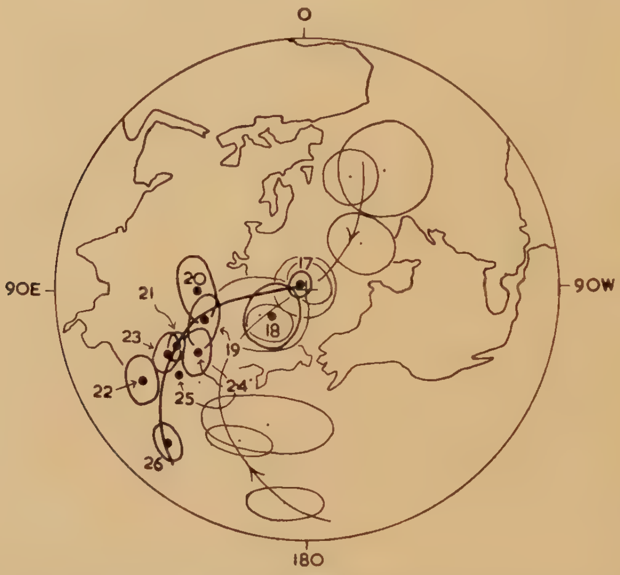
Age	Formation	Mean magnetic direction			Sampling area		Ancient pole position			
		D	I	α	Lat.	Long.	Lat.	Long.	δm	δp
Miocene	5. Iceland lavas	1·5	+77·8	5·5	65·2N	20W	88·6N	5·2E	10·3	9·6
Oligocene	6. Intrusives of Central France	21	+57	11·0	46N	3E	73N	119E	16	12
Eocene	7. Antrim lavas	14	+60	5	55N	6W	74N	133E	8	6
Triassic	8. Keuper Marls and sst.*	33	+27	12	53N	2W	43N	131E	12	7
Permian	9. Exeter Volcanic Series	9	+ 9	20	51N	4W	43N	164E	20	10
Carboniferous	10. Derbyshire Sedimentary rocks*	26	+37	—	53N	2W	51N	143E	—	—
	11. Derbyshire igneous rocks*	26	+43	—	53N	2W	55N	148E	—	—
Devonian	12. O.R.S. of the Welsh Cuvette	19	− 2	10	52N	3W	34N	156E	10	5
Cambrian	13. Caerbwby Sandstone of Wales	7	−39	8	52N	5W	15N	173E	10	7
Upper Pre-Cambrian	14. Longmyndian of Shropshire	294	−29	12	53N	3W	2N	120W	13	7
	15. Upper Torridonian of Scotland	303	−44	5	58N	6W	6S	137W	6	4
	16. Lower Torridonian	307	+34	7	58N	6W	35N	118W	8	5

The symbols have the same meaning as in table 1. Only three Tertiary results are given but many more can be obtained by reference to Hospers (1955). In some cases in this and table 3 the pole positions have not been calculated by the workers who have made the palaeomagnetic observations, and this has been done by the author. These cases are indicated by an asterisk.

In Lower Carboniferous times Belshe's results (reported in Runcorn 1955) suggest that the pole was near Sakahlin. In the Devonian period the pole appears to have been situated just to the south-east of present day Honshu, and in Cambrian times it lay in the West Pacific near the equator (Creer *et al.* 1957).

The Applecross and Aultbea Group of the Torridonian Sandstone Series of Scotland and the Longmyndian of Shropshire (Creer *et al.* 1957) which are of late Pre-Cambrian age have magnetization consistent with a pole in the Central Pacific. The lowest group, the Diabaig Group, of the Torridonian gives a pole in California.

Fig. 7



The pole positions given by the U.S.A. results are plotted on a Lambert's equal-area polar projection. The poles from Australia and Europe are added in thinner line. The poles are numbered as follows: 17, Upper Tertiary; 18, Cretaceous; 19, 20, Triassic; 21, 22, 23, Permian; 24, 25, Carboniferous; 26, Silurian.

2.3. *North America Results*

The results are summarized in table 3 and plotted in fig. 7.

The varved clays of New England, covering the period from 15 000 to 9500 years ago (Johnson *et al.* 1948), and Miocene to Pliocene Columbia River basalts of Oregon (Campbell and Runcorn 1956) give mean directions parallel to the dipole field, and the pole coincides with the present geographic pole.

According to Runcorn (1956 a) the Cretaceous Dakota Sandstones of Arizona give a pole near the New Siberian Islands. The pole from the Triassic Springdale and Moenkopi Sandstones is near Lake Baikal (Runcorn 1956 a). Preliminary results from Triassic lava flows from the

Table 3. Pole Positions from the American Results

Age	Formation	Mean magnetic direction			Sampling area		Ancient pole position			
		D	*I*	α	Lat.	Long.	Lat.	Long.	δ*m*	δ*p*
Miocene and Pliocene	17. Columbia River Basalts*, reversed flows only.	3·1	−66·0	10·7	47N	118W	87N	76W	17·4	14·3
Cretaceous	18. Dakota Sandstone	344	+62	7	36N	113W	77N	127E	11	9
Triassic	19. Springdale and Moenkopi Sandstones	338	+16	9	36N	113W	55N	107E	9	5
	20. Lavas of the Connecticut Valley	10	+14	11	42N	73W	54N	90E	11	6
Permian	21. Supai Beds (Graham's data)*	330	− 3	5	36N	113W	43N	113E	5	3
	22. Supai Beds (Runcorn's data)	313	−23	8	36N	113W	26N	119E	8	6
	23. Supai Beds (Doell's data)	326	− 8	7	36N	113W	39N	115E	7	4
Pennsylvanian	24. Naco Sandstones	330	+ 3	3	36N	113N	49N	120E	8	4
Mississippian	25. Barnett shales of Texas	—	—	—	—	—	39N	124E	—	—
Silurian	26. Rosehill Beds	322	−39	5	40N	78W	19N	138E	6	4

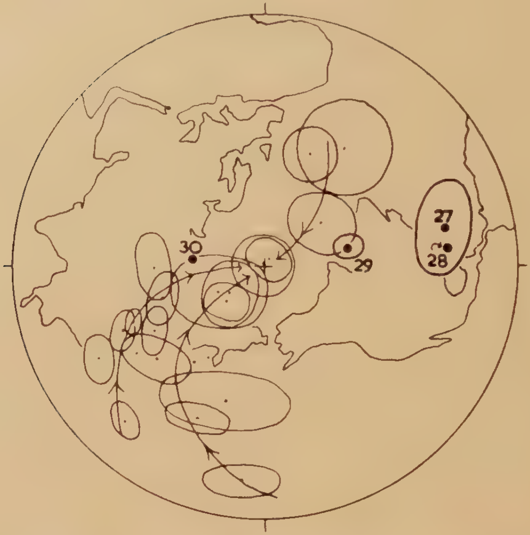
Symbols as in previous tables.

Connecticut Valley give a similar pole position (Banks and Irving 1956, unpublished results).

Results by three workers are available for the Supai beds of Permian age. The pole calculated from Graham's (1955) data is very close to that given independently by Doell (1955). Runcorn's pole (1956 a) is a small distance away to the south, the error circle just touching that of Doell's determination but is 7° from the error circle of Graham's result. These differences are probably due to sampling inadequacies (Doell 1955). For the Naco Sandstones of Arizona (Pennsylvannian) the pole is in Manchukuo (Runcorn 1956 a), and for the Barnett shales of Texas (Mississippian) it is in Korea Bay (Martinez and Howell 1956). The Silurian Rosehill Beds studied by Graham (1949) give a pole near the Philippine archipelago.

Several results from the Pre-Cambrian of America have been reported but comparison with the British results is at the moment impracticable.

Fig. 8



Pole positions calculated from Indian, African and South American data. Lambert's polar equal-area projection is used and the poles are numbered as follows: 27, 28, Deccan Traps; 29, Karroo basalts; 30, Dolerite dykes of Parana.

Table 4. Pole Positions from Results from India, Africa, and Brazil

Period	Formation	Mean magnetic direction			Sampling area		Ancient pole position			
		D	*I*	α	Lat.	Long.	Lat.	Long.	δ*m*	δ*p*
Cretaceous to Eocene	27. Deccan Traps (The author's determination 1954, 1956 b)	329	−56	10	18N	74E	28N	78W	15	10
	28. Deccan Traps (Determination by Clegg *et al.*, see Clegg 1956)	—	—	—	—	—	28N	85W	—	—
Jurassic	29. Karroo basalts of Rhodesia	330	−40	4·6	18S	25E	62N	77W	5	4
	30. Parana dykes of Brazil	22	−60	—	26S	49W	67N	83E	—	—

Symbols as in previous tables.

2.4. *Results from other Regions*

Nairn (1956) has reported that the magnetization of the Jurassic basalts in the vicinity of the Victoria Falls suggest that the pole was in Hudson Bay at this time. The pole consistent with the magnetization of the Deccan Traps (Cretaceous to Eocene) is near Florida (Irving 1954, 1956 b). This result has since been independently confirmed by Clegg *et al.* (1956), the poles lying within 6° of each other and well within the errors (fig. 8 and table 4). Samples from the Jurassic dolerite sills of Parana give a pole near the mouth of the Yenesei River.

§ 3. POLAR WANDERING

In Iceland, Britain, Oregon and Victoria during the Upper Tertiary and later epochs the geomagnetic field has, on average, been similar to that of a geocentric axial dipole, and the geomagnetic pole has been the present geographic pole. It seems unlikely that appreciable polar wandering or land movement between these regions has occurred during this time, and the requirements of hypothesis A, are satisfied. The large-scale polar wandering postulated by Kreichgauer (1902), Köppen and Wegener (1924) and Milankovitch (1938), in the Upper Tertiary and Pleistocene now seems out of the question. This was first pointed out by Hospers (1955) on the basis of the European and Icelandic evidence, and the later results from Oregon and Victoria reinforce his argument.

Prior to Miocene times the situation is more complicated since the poles do not coincide with the present geographic pole. The generalized pole paths with respect to Australia, Europe and North America are shown in figs. 6 and 7. The true pole paths are likely to be more complicated than is depicted ; for instance, the Carboniferous poles from Britain and North America are in advance of the Permian poles, and as sampling becomes more adequate many detailed irregularities of this type are likely to arise. These curves represent, to a first approximation the movement of the pole relative to the particular sampling region. This movement may be due to wandering of the polar axis or movement of the sampling region relative to the Earth as a whole or to both causes. In this section the first of these (polar wandering) is considered, whereas the second (continental drift) is discussed in § 4.

Early work on the stability of the Earth's axis of rotation under the influence of geological changes such as epeirogenesis (Darwin 1877, Thomson 1890, see also a review by Munk 1956) was indecisive largely because of the inadequacies of the Earth models used. Recently Gold (1955) and Munk (1956) with a more adequate knowledge of the mechanical properties of the Earth at their disposal have shown rather convincingly that geological causes could distort the figure of the Earth sufficiently to cause large-scale polar wandering. Gold suggests that polar wandering of this type is likely to be discontinuous, so that long periods of negligible change are separated by geologically short periods during which polar wandering was rapid. Changes of many degrees in 10^5 or 10^6 years appear to be possible. Large changes in magnetic directions (discounting reversals) in a continuous rock sequence have so far only been observed in the Torridonian Sandstone Series, (Irving and Runcorn 1957). The lowest or Diabaig Group in this Series has NW positive magnetizations for the most part, and the overlying Applecross and Aultbea Groups have NW negative or SE positive directions (table 2, see also Runcorn 1955, fig. 9). The change occurs not at the junction of the Diabaig and Applecross beds but within the former, the uppermost 100 feet of the Diabaig sequence being magnetized in the same direction as the remainder of the Torridonian. The magnetic change occurs just before the stratigraphic break. Below and above this level, the directions, although different, persist for 2000 ft and 14 000 ft respectively, which is as far as sampling has been carried. This direction change of 78° and attendant pole movement of 46° (fig. 6) is discontinuous, occurring rapidly compared with the time of duration of the stable direction and pole position. These observations agree qualitatively with Gold's prediction.

The hypothesis of polar wandering, combined with the assumption that the magnetic and rotational axes have coincided on average throughout geological time, has three consequences.

1. The pole positions for rocks of the same age from different places on the Earth should be coincident.

2. During any one geological period the past climate at any place should be broadly consistent with the geomagnetic latitude deduced from the angle of magnetic dip observed in rocks of the *same* age in the *same* general region.

3. During any one geological period the indications of palaeoclimatology at *all* places on the Earth should be consistent with the latitude deduced from a pole position which has been calculated from the palaeomagnetic results from a *single* region.

If the first prediction is borne out by observation it is unlikely that continental drift has occurred, but the pole positions determined in this fashion need not be identified with the geographic poles. If the second point is found to be correct the correlation, on average, of the magnetic and rotational axes seems likely, and the magnetic poles are, in fact, the geographic poles also. Finally, if the observations satisfy the third consequence as well as the former two, then continental drift seems doubly unlikely, and polar wandering only has occurred.

On the other hand, if the land-masses have moved relative to one another, the magnetic and rotational axes remaining coincident, it follows that the second of the above points will hold, but the others will not; the curve of polar movement given from results from different continents will not be the same, and the palaeoclimatic evidence at all places on the Earth will not agree with the pole positions given by the palaeomagnetic results from any single continent. These three points are now considered in order.

Prior to Miocene times the pole positions calculated from rocks laid down at the *same* period but in *different* continents do not fall at the same place on the Earth's surface. The largest discrepancy is between the poles calculated from the northern and southern continents; for instance the pole calculated from magnetic directions in the dolerite sills of Tasmania are at least 50° away from the poles given from measurements on rocks of similar age from Europe or the U.S.A. The poles from the Australian results are in approximately opposite longitudes from those from Europe and America. A second discrepancy is between the Palaeozoic and Triassic results from Britain and the U.S.A. Without exception the poles derived from the American data are to the west or north-west of those from Europe (fig. 7). The pole paths converge on the present pole during the Tertiary. At first, when only a few pole positions were available from North America, these differences were considered unimportant (Graham 1955, Runcorn 1956 a). Many more results have now been obtained and it is clear that there is a significant displacement with respect to the European poles (Creer *et al.* 1957, Runcorn 1956 c, Irving 1956 b). This is illustrated in table 5 in which the separation of Permian and Triassic poles obtained from either side of the Atlantic are compared. Finally, there is disagreement between results from the southern continents (fig. 8) (Nairn 1956). Clearly, the first implication of the hypothesis of polar wandering is contradicted by the palaeomagnetic data.

Table 5. Comparison of Pole positions from the Permian and Triassic and Britain and the U.S.A.

	Triassic		Permian		
	Runcorn	Banks and Irving	Graham	Doell	Runcorn
Present distribution	6	11	16	13	13
Du Toit's reconstruction	6	8	16	12	9
Carey's reconstruction	0	0	5	0	0

This table gives the separation in degrees of the perimeters of the error circles of the pole determinations from Britain and U.S.A. calculated for the present position of these countries, and also the positions postulated by Du Toit and Carey for these periods. From Britain there are single determinations from the Permian and Triassic; from the U.S.A. there are three and two respectively.

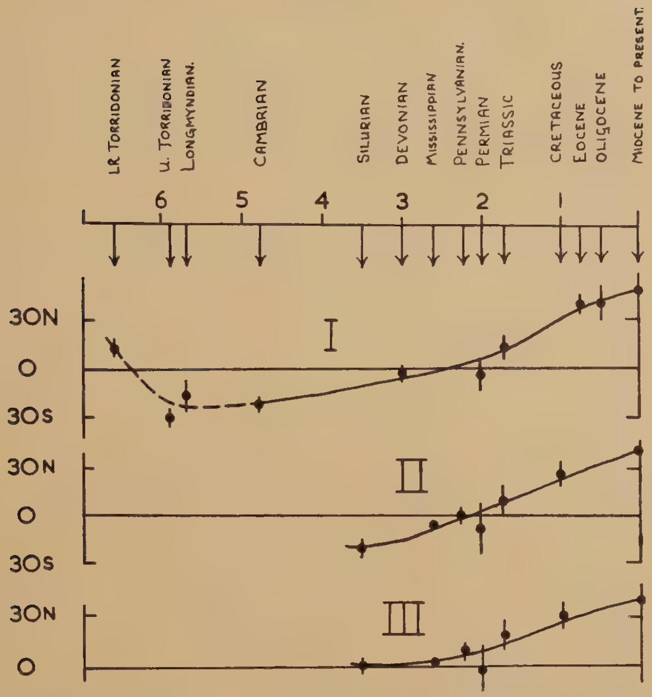
The palaeoclimatic aspects are now considered. See also Runcorn (1956 b) and Irving (1956 b) for a fuller discussion. Some of the characteristics of rocks may be regarded as indicative of the climatic conditions at the time of deposition. From this point of view continental deposits are the most interesting.

Climate is, in general, determined by the intensity of solar radiation and by latitude. The changes in climate caused by fluctuations in solar radiation will be general for the whole Earth, but the latitude effect will remain, although perhaps less at some times than at others. Large variations due to irregularities in ocean currents, the varying size and topography of land-masses will be superposed on the latitude effect. Clearly there are many exceptional circumstances and without very detailed study all that can be done is to obtain broad climatic indications and from these to infer the probable latitude. The most that can be hoped for when comparing this evidence with the palaeomagnetic observations is either a general agreement or a gross inconsistency.

The variations in geomagnetic latitude for Britain and America are given in fig. 9. The occurrence in Britain of red sandstones and coral reefs in the Devonian, coal measures and coral reefs in the Carboniferous, red sandstones and salt deposits in the Triassic, and coral reefs in the Jurassic, suggest low or intermediate latitudes in the Upper Palaeozoic and Mesozoic. This is in agreement with the magnetic latitude, the agreement being as good as could be anticipated in view of the qualitative nature of the palaeoclimatic data. For the U.S.A. two curves are constructed, one each for the eastern (II) and western (III) parts. These curves are widely separated in the Palaeozoic when the geomagnetic pole lay to the west, but later close together. Again there is qualitative agreement with palaeoclimatology. During the whole of the time from Silurian to Triassic the stratigraphical record is full of occurrences of red beds, salt deposits, thick coal seams, coral limestones and dolomites indicating low or intermediate latitude, and this is mirrored by geomagnetic latitudes of 0° to 30°. Particularly impressive is the coincidence, both in Britain and the Eastern United States, during Carboniferous times of low geomagnetic latitude with the deposition of coal measures of a type which have been generally regarded by geologists to have been laid down in regions of high temperature and heavy rainfall comparable with the climate of present day equatorial regions. The palaeomagnetic results from Australia reveal a similar correspondence between the palaeomagnetic latitude and the local palaeoclimate. For instance, the lavas and varves in the glacial Kuttung Series exhibit steep magnetic dip. Similarly the steep magnetic dip of the Tasmanian dolerites give a geomagnetic latitude of 65–80° for South Eastern Australia sometime during the Cretaceous and Jurassic (Irving 1956 a). The climatic evidence from this region (reviewed in David 1950, p. 515) suggests cool even glacial conditions during these periods.

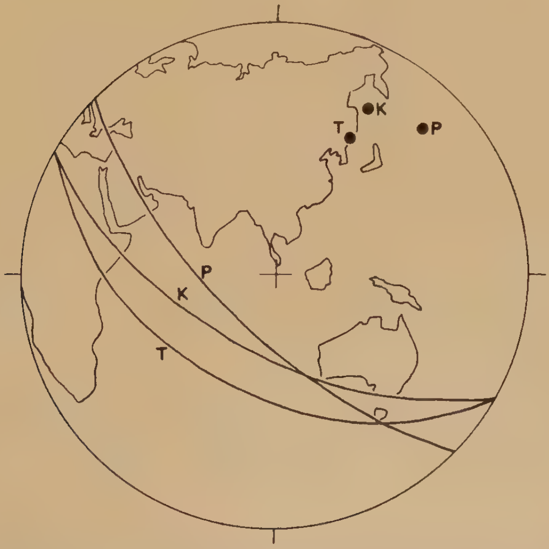
It remains to consider to what extent the palaeoclimatic evidence from one part of world is consistent with the palaeomagnetic evidence from another. In many cases the two lines of evidence are in strong conflict. Two examples are given here. The Carboniferous, Permian and Triassic poles derived from the European data are all near the North Eastern coast

Fig. 9



The Variation in Geomagnetic Latitude in Britain (I), Eastern U.S.A. (II) and the Western U.S.A. (III). The 'tails' on the points correspond to the zones of confidence in figs. 6 and 7, and the curve has been estimated as a best fit by eye to the calculated points. The time scale is approximately correct for Cambrian and later periods, but since the absolute age of the older formations is not known the form of the earlier part of the curve is unreliable and is only added for completeness.

Fig. 10



The poles and equators in Carboniferous (K) Permian (P) and Triassic (T) times. Lambert's equatorial equal-area projection is used.

of Asia (fig. 10) not far from Northern China, where however, from the Carboniferous to the Jurassic there is a full sequence of terrestrial deposits exhibiting characteristics uniformly indicating low or intermediate latitude. Glacial beds which are found elsewhere in the world in the Carboniferous and Permian, and which would be anticipated from the high latitude, are entirely absent. The equator in Carboniferous and Permian times passes through the southern regions of Australia where in contrast thick glacial beds are found.

Prior to Tertiary times contemporaneous pole positions from different continents never agree, and the pole positions although consistent with the evidence of past climates in the same region do not correspond with that from other parts of the Earth. Of the three requirements of the hypothesis of polar wandering (hypothesis B) only one, the second, is satisfied. Of the remaining hypothesese the fourth (D) seems the more likely for this reason. If independent continental movement occurred without a general polar shift (hypothesis C) it is not to be expected that the polar curves for different continents will show any marked similarity. The European and North American curves (fig. 7) are, however, similar in form and direction. It seems necessary to postulate two effects ; a general polar shift relative to the whole Earth to explain this similarity and perhaps comparable in character to that envisaged by Gold (1955), and secondly, movements of the continents relative to each other, accounting for the disparity in position of the polar curves and the inconsistencies between these and the African, Australian and Indian poles.

These arguments depend for their validity on the dipole hypothesis which is an extrapolation back into remote geological time of the known behaviour of the field over the past 20×10^6 years. If this idea is abandoned the behaviour of the field during and since Miocene times has to be regarded as exceptional, so that in the more remote past the lines of force had a much more complicated distribution. In this case the pole positions calculated from Pre-Miocene palaeomagnetic results are meaningless, and there is of course no need to consider the possibility either of polar wandering or continental drift. The dipole hypothesis is however consistent with modern ideas about the origin of the geomagnetic field (Runcorn 1954), and the good agreement between the palaeoclimatic and palaeomagnetic latitude in the same region during the same geological period is difficult to reconcile with any except an average axial dipole field.

On these grounds, and with these reservations, it seems reasonable to proceed with the dipole hypothesis, and to consider the amount of continental drift which the palaeomagnetic results thereby imply.

§ 4. CONTINENTAL DRIFT

When complete results are forthcoming from many parts of the world it ought to be possible to produce palaeogeographic reconstructions from them, but it will be many years before there is sufficient information to do this satisfactorily. However, as an interim measure, it is of interest to see to what extent the present data is consistent with the palaeographic reconstructions provided by the various exponents of continental drift.

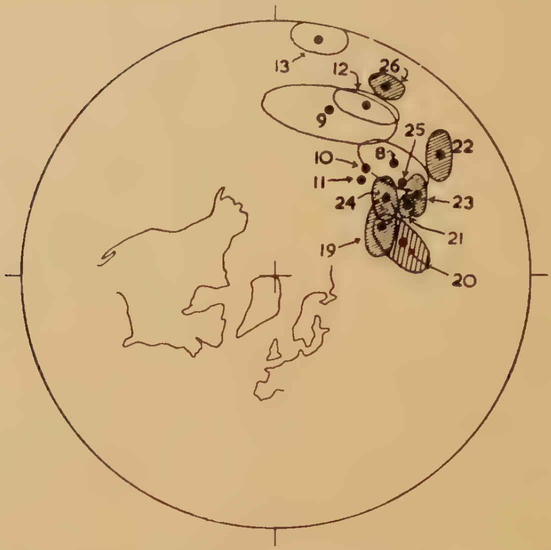
The test of drift reconstructions may be achieved by recalculating the pole positions not, as hitherto, with respect to the present positions of the sampling area, but relative to the past positions postulated by these reconstructions. The ‘ ancient ’ coordinates of the sampling area can be read from these maps, and the ancient pole positions accurately calculated. If the reconstructions are valid, the discrepancies in the pole positions obtained from rocks of the same period from different continents should disappear.

The co-ordinates systems used by Wegener (1924) and Köppen and Wegener (1924) are too crude for the present purposes, but the reconstructions Du Toit (1937) King (1956) and Carey (1956 a, b) are sufficiently precise. Wegener's reconstructions embrace both Northern and Southern continents uniting them in a single ‘ Pangaea ’. Du Toit and King prefer to imagine two primaeval continents, ‘ Laurasia ’ and ‘ Gondwanaland ’, and has provided separate reconstructions of these in independent coordinates ; in these cases palaeomagnetic results from one hemisphere cannot be applied to a reconstruction of the other hemispheres. Carey, on the other hand, has returned to the earlier idea of ‘ Pangaea ’, and inter-hemisphere comparisons will eventually be possible using his maps. A fuller discussion of the test of drift reconstructions has been given previously by Irving (1956 c). Three reconstructions only are considered here as examples. These are the northern hemisphere reconstructions of Du Toit (1937, p. 134) and Carey (1956 a), and the Gondwanaland reconstruction of Du Toit (1937, p. 58).

Laurasia is considered first. Figure 11 gives the pre-drift positions of Europe and North America according to Du Toit, and the poles calculated from these. Approximately contemporaneous results from the Carboniferous, Triassic and Permian are available from both regions, but in the former case no errors have been published. Thus, strict comparisons are possible between the Permian and Triassic only, and the angular distance between the perimeters of the error circles on the present distribution of the continents, and on the two reconstructions as given in table 5. Du Toit moves North America towards Europe so that the Atlantic is about half closed, Europe is displaced a little in a northerly direction with respect to North America. The fit of the poles is not appreciably better than on the present distribution.

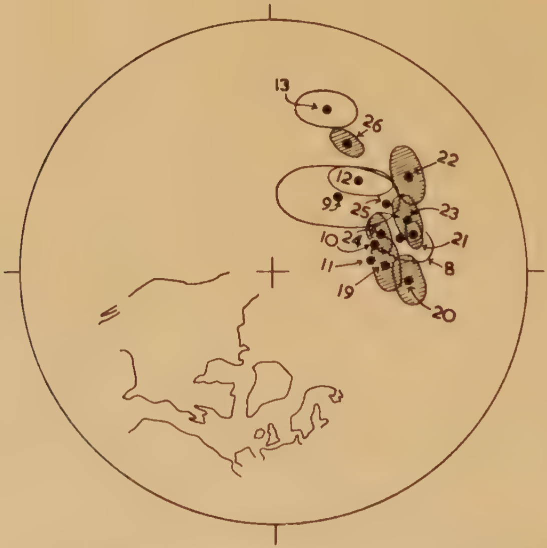
Figure 12 gives Carey's Laurasia reconstruction. He moves Europe a considerable distance northward with respect to North America and closes the Atlantic more or less completely. This motion is more complicated than that advocated by Du Toit, and, with one exception, succeeds in bringing the Permian and Triassic poles together at the present statistical level (table 5). In the single exception—Graham's Permian determination—the residual separation is now 5°, over three times less than the separation

Fig. 11



Pole positions calculated from Du Toit's reconstruction of Laurasia. The poles are numbered as in figs. 6 and 7. The American poles are shaded. Lambert's equal-area polar projection is used.

Fig. 12



Pole positions calculated from Carey's reconstruction of the northern continents. Legend as for fig. 11.

on the present continental distribution. As an initial approximation Carey's reconstruction of Laurasia fits the palaeomagnetic data in a rather attractive fashion. Carey's reconstruction is based on assumptions about the nature of orogenic belts which are remote from any geomagnetic considerations. Another feature of fig. 12 is that although the poles from the same period are drawn together a progressive difference as between earlier and later periods remains. This may be interpreted as the general polar shift referred to in hypothesis D, and its presence is consistent with the conclusions of the last section.

The southern land masses are now considered. It is postulated, by the supporters of continental drift, that the present land masses of South America, Africa, peninsular India, Arabia, Australia and Antarctica were once united in a single large continent, which was broken up and dispersed in later Mesozoic and Tertiary times. The greatest of all pole discrepancies should be revealed between these fragments, and in particular, peninsular India, which is supposed to have suffered at least 5000 miles latitudinal translation, should disclose this effect most readily. As with Laurasia, there is considerable variety of opinion amongst supporters of drift as to the detailed physical geography of Gondwanaland, and the mode and occasion of its partition. As an example Du Toit's map which represents Gondwanaland during the Palaeozoic Era is taken. Only two Palaeozoic results are available ; the result from the Kuttung Volcanics, and the data of Gough's (1956) from the Pilansberg dykes. The age of the latter is so uncertain that the result is not considered here. There are 5 pole positions from the Mesozoic and Lower Tertiary and these together with the Kuttung pole are plotted on fig. 13. This does not constitute an absolutely fair test of Du Toit's Palaeozoic reconstruction. However partition was not initiated till the Jurassic, became appreciable in the Cretaceous, and complete separation of the fragments was not achieved till Cretaceous to Tertiary times (Du Toit 1937, p. 99). If this were true inclinations would be greater than at present and the poles although not necessarily coincident should be closer together on Du Toit's map. Comparison of figs. 8 and 13 shows that this is so. The separation of the Tasmanian dolerite and Karroo basalt poles although less is still considerable.

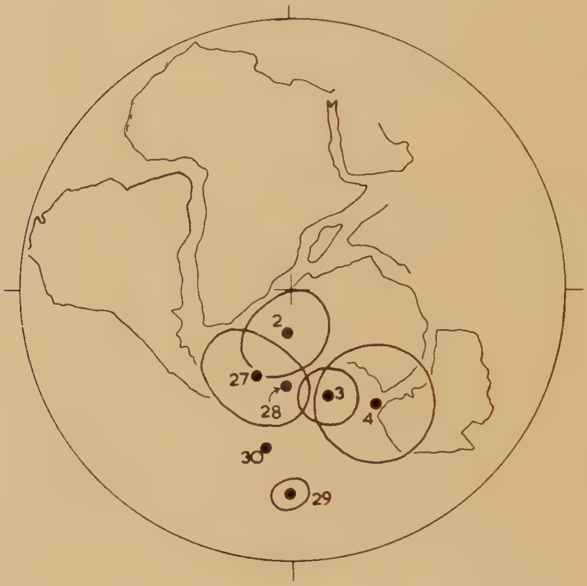
In the future it ought to be possible to draw palaeographic maps based on magnetic data only. The success attending these efforts will depend to a great extent on the solution of two difficulties.

For any single geological period it is convenient to regard the pole as fixed and the continents as moveable. The magnetic dip I gives the colatitude p of the sampling area by the following equation,

$$\cot p = \tfrac{1}{2} \tan I.$$

If the possibility of drift is admitted, both rotations and translations of the continents are equally likely, so that the declination does not fix the longitude of the sampling area, and any position on the small circle of radius p around the pole will satisfy the palaeomagnetic data provided the land mass is rotated suitably. Similarly, the nth sampling region with magnetic dip I_n may have been situated anywhere on a small circle of radius p_n, so, for given sets of data from several continents an infinite number of continental arrangements are possible. This is illustrated in fig. 14, using results from the Tasmanian dolerites, and some results which have been obtained from the Parana dykes and the Karroo basalts (Nairn 1956), which for the sake of this illustration are assumed to belong to the same geological period. The poles are, in all cases fixed at the centre of the projection. The colatitudes given by the magnetic results are 10° for Tasmania, 49° for southern Brazil and 60° for Central Africa, and the land masses are rotated through the declination angle so that the horizontal component of magnetization lies along a meridian. These rotations are 35° clockwise, 22° anti-clockwise, and 30° clockwise respectively. In fig. 14(b) the relative longitudes are those of the present day. The remaining diagrams give other solutions compatible with the magnetic data. Clearly, the situations in figs. 14 (a) and (c) where the continents are superposed, are absurd, Nevertheless, there remains a very large

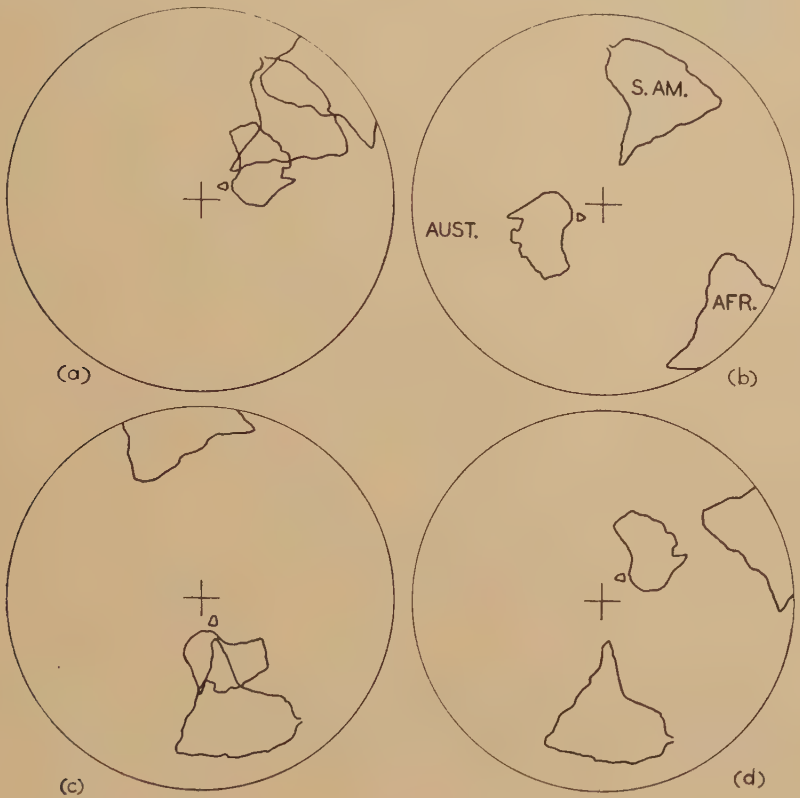
Fig. 13



Pole positions calculated from Du Toit's reconstruction of Gondwanaland. The stereographic projection is used. The poles are numbered as follows: 2, Lower Basalts of Victoria; 3, Tasmanian dolerites; 4, Kuttung volcanics; 27, 28, Deccan Traps; 29, Karroo basalts; 30, Parana dykes.

number of solutions of the type 14 (*b*) and (*d*) between which the palaeomagnetic data cannot discriminate. This number may be reduced when results from adjacent geological periods (that is, older and younger rocks) are considered, but it is unlikely that palaeomagnetic solutions will be unique.

Fig. 14



Reconstructed positions of the three southern continents using the palaeomagnetic data. Lambert's equal-area polar projections are used. The poles calculated from the palaeomagnetic data are placed together at the pole of the projection and the continents moved accordingly.

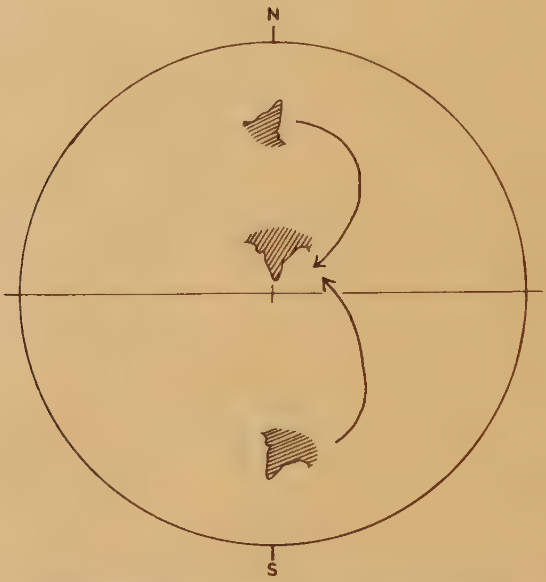
The second difficulty arises through the occurrence of reversals of magnetization. Because of the uncertainty surrounding the interpretation of reversals we cannot say to which of the geomagnetic poles the north-seeking polarizations of a rock formation points; we cannot say whether the sampling area was situated in what was at the time of deposition the Northern or Southern Hemisphere. The results from India provide a good example of this dilemma. The author's determinations in the Deccan Traps give a mean direction of 149°, +56° and reversals occur

(Irving 1956 b). Even if there were no reversals the doubt about the sign of the magnetic field at deposition still remains, since there is the possibility of a whole rock formation developing self-reversed magnetization. Thus in explaining the results from India two alternatives arise (fig. 15).

(i) That peninsular India has moved from a latitude of 54°N rotating clockwise through 149°.

(ii) That India has moved from a latitude of 54°S and rotated 28° anticlockwise.

Fig. 15



The alternative positions of peninsular India suggested for the end of the Mesozoic or beginning of Tertiary times by the palaeomagnetic evidence. Lambert's equal-area equatorial projection is used.

The reconstructions given in figs. 14 and 15 are intended only as an illustration of the palaeomagnetic method, and are not a serious attempt at a valid reconstruction. It seems likely that the interpretation of world-wide palaeomagnetic data will present geometrical problems of great complexity, the solutions to which may not be unambiguous.

Some of these ambiguities may have to be finally settled by reference to geology. It should be possible to eliminate many solutions, on the grounds that they are contrary to the evidence of geological structure and rock facies. For instance, of the two alternative positions for India the southern hemisphere one seems the more likely because of the presence to the north of the Tertiary fold belt of the Himalaya.

The *interpretation* of the palaeomagnetic data *in terms of the dipole hypothesis* leads us to suppose that continental drift has occurred. In some cases this evidence is consistent with the inter-continental movements which have been postulated independently from entirely different evidence. Particularly impressive is the unification (with one exception) of the contemporaneous pole positions from North America and Europe by Carey's reassembly of these continents. Also the palaeomagnetic inclinations recorded from Pre-Miocene rocks from the southern continents are all higher than those appropriate to their present latitude as drift reconstructions require. Nevertheless we are a very long way indeed from being compelled to believe that large scale polar wandering and continental drift as envisaged by Wegener, has, in fact occurred, but this new evidence means that the possibility of these cannot be ignored in palaeogeographic discussions. Gold (1955) and Munk (1956) have re-discussed the problem of polar wandering to which there seems to be no geophysical objections as was sometimes thought. A similar re-examination of the geophysical objections to continental drift raised by Jeffreys (1952) is indicated.

Returning to the initial propositions A, B, C and D, we may summarize as follows. Hypothesis A (that is no polar wandering or drift) is valid for Upper Tertiary and later epochs. For Pre-Miocene times hypotheses C and D are applicable, and of these D is the more likely. There is nothing in the results which make us suppose that polar wandering or continental drift have been processes operating throughout all Pre-Miocene periods. In fact, there are some points which suggest that polar wandering may have been discontinuous, occurring only during short periods separated by long periods of quiet during which no movements occurred. On this view the past 20×10^6 years is not exceptional but has simply been a period of comparative inactivity (polar to drift inactivity that is) such as has occurred many times previously.

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Some Recent Palaeomagnetic Measurements made at Imperial College, London

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Introduction

This paper gives a brief report of some recent palaeomagnetic measurements made by the Group working in the Physics Department at the Imperial College of Science and Technology, London. The present research programme includes investigations of Triassic red sandstones from France and Spain, of lavas from the Deccan Traps in India, and of igneous rocks and baked sediments, mostly Carboniferous in age, from a number of areas in Britain.

§ 1. British Igneous Rocks and Baked Sediments

The study of the baked sediments found in close contact with igneous rocks is one of considerable palaeomagnetic interest, and a large number of baked sediments and associated igneous rocks have been obtained from Scotland and, in collaboration with Mr. J. C. Belshé of the Department of Geodesy and Geophysics Cambridge, from various sites in the English Midlands. The collection includes :

(*a*) Baked and igneous rocks from six sites extending over a distance of 30 miles between the Clee Hills and Walsall, probably belonging to the late Carboniferous,

(*b*) Baked rocks associated with Upper Carboniferous intrusions from Tideswelldale in Derbyshire, and

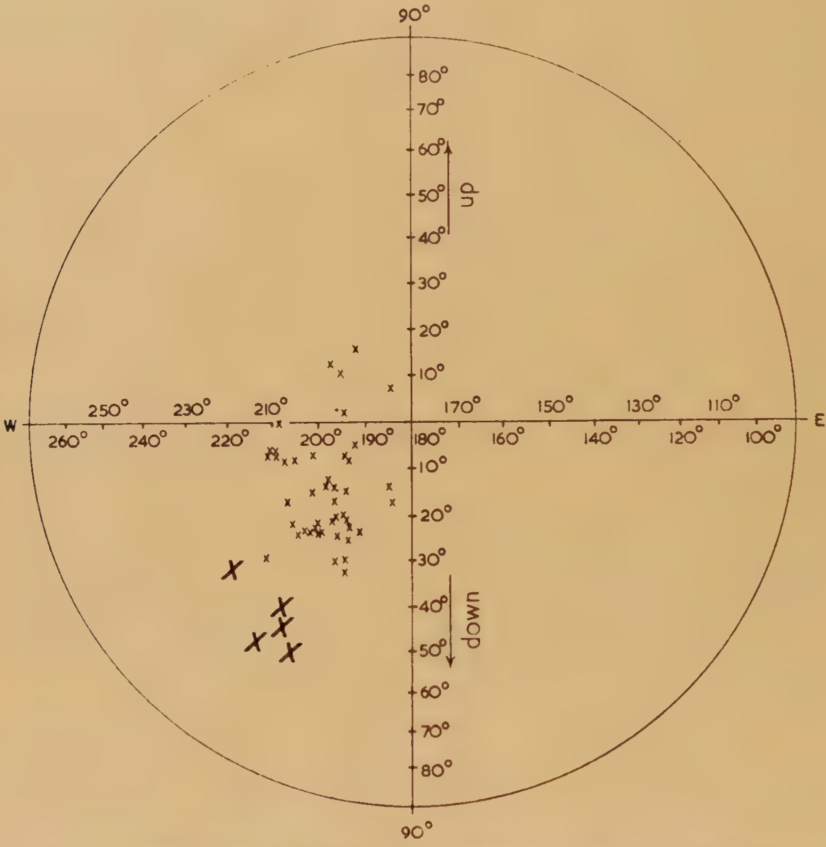
(*c*) A series of lava flows, Lower Carboniferous in age, exposed along the shore at Kinghorn, Fifeshire. These latter beds are numbered consecutively 1–65 from the bottom upwards in the following text.

Table 1

	Declination	Dip
Clee Hill	N 200° E	+15° down
Tideswelldale	N 218° E	+36° down
Kinghorn Flows 41–46	N 26° E	−42° up
,, 48–54	N 200° E	+38° down
,, 64–65	N 20° E	+15° down

The results are plotted in figs. 1 and 2 and the mean directions of magnetization are shown in table 1. It is evident that the rocks from the English Midlands (Clee Hill and Tideswelldale) have a marked preferential axis of magnetization, dipping downwards in a direction some 20° to the East of South. The Scottish lavas, with the exception of the two uppermost beds (64 and 65) are magnetized along a similar axis, but have steeper dips. There is a magnetic reversal in the middle of the succession. The fact that beds 64 and 65 are magnetized in a direction much closer to the present geomagnetic field than the remainder of the rocks sampled may be due to instability, and the results as a whole can evidently best be explained on the supposition that Britain, during the Carboniferous Period, occupied a position to the South of the equator.

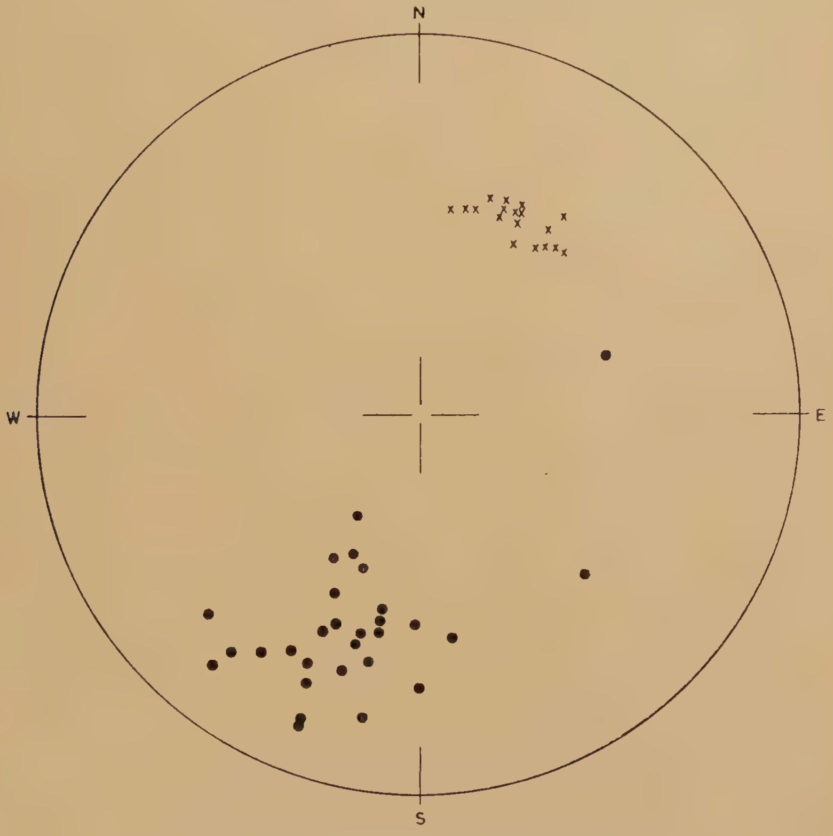
Fig. 1



Equatorial (equal area) projection. Baked rocks from English Midlands.
× From Clee Hill and Walsall area.
╳ From Tideswelldale.

It is disturbing to compare these measurements with those made by J. C. Belshé (1957), in an extensive survey of British Carboniferous rocks reported elsewhere in this volume. Belshé examined a large number of unbaked sediments and a few igneous rocks, and found the mean direction of magnetization to be N 26° E with a downward dip of 37°. This differs by rather more than 50° from the directions given in table 1 for the English rocks, and by about 80° from those given for the Scottish lavas. Such a discrepancy is hard to explain. Consideration of the time scales involved evidently precludes the possibility of its being due to large secular variation, for Belshé's collection and ours each included rocks differing in age by millions of years. It could arise from the incorrect dating of some of the formations sampled, but this, in view of the reliable geological evidence, seems to be very unlikely.

Fig. 2



Polar (equal area) projection. Kinghorn.
× Flows 41–46 (upwards).
● Flows 50–54 (downwards).

We appear to be left, then, with four possible explanations—viz :

(*a*) That some of the rocks acquired their present magnetization at a time later than the Carboniferous. It is hardly conceivable, however, that this can be true of the baked sediments, for the fact that the intensity of magnetization invariably falls off with distance from the contact provides overwhelming evidence to suggest that the magnetism was acquired at the time of emplacement of the molten magma.

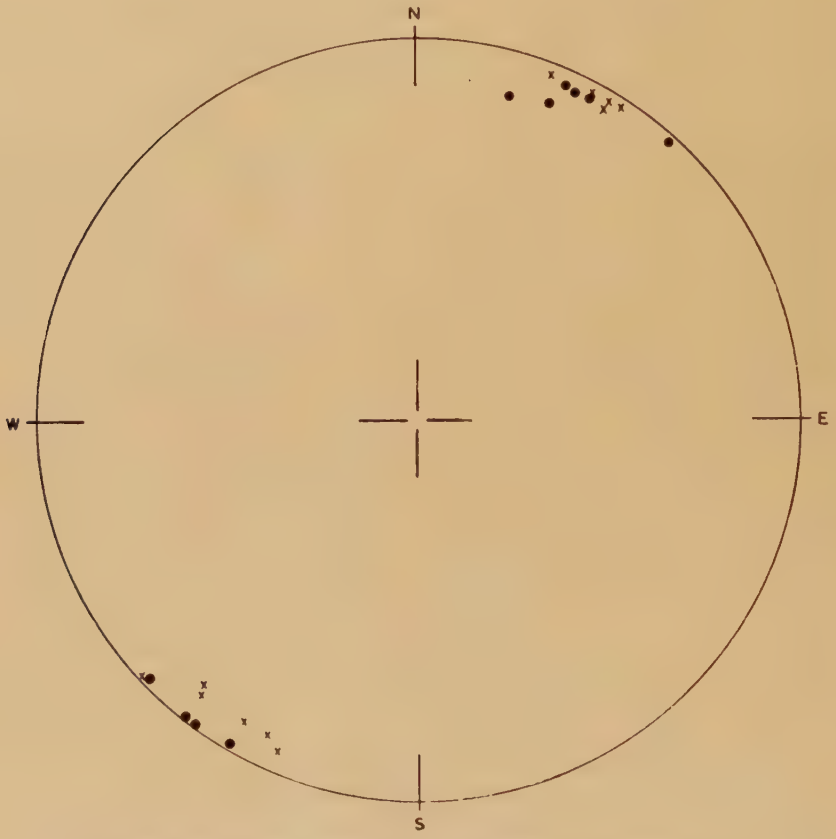
(*b*) That by some unknown physiochemical process some of the rocks acquired, at the time when they were magnetized, magnetic polarizations in a direction oblique to that of the Earth's field.

(*c*) That a large change occurred in the position of the British land mass relative to the poles at some time during the Carboniferous Period.

(*d*) That over a period of millions of years the Earth's field had a persistent mean direction which differed substantially from that of an axial dipole.

Further work on igneous and baked rocks of the Carboniferous Period from other British sites is in progress.

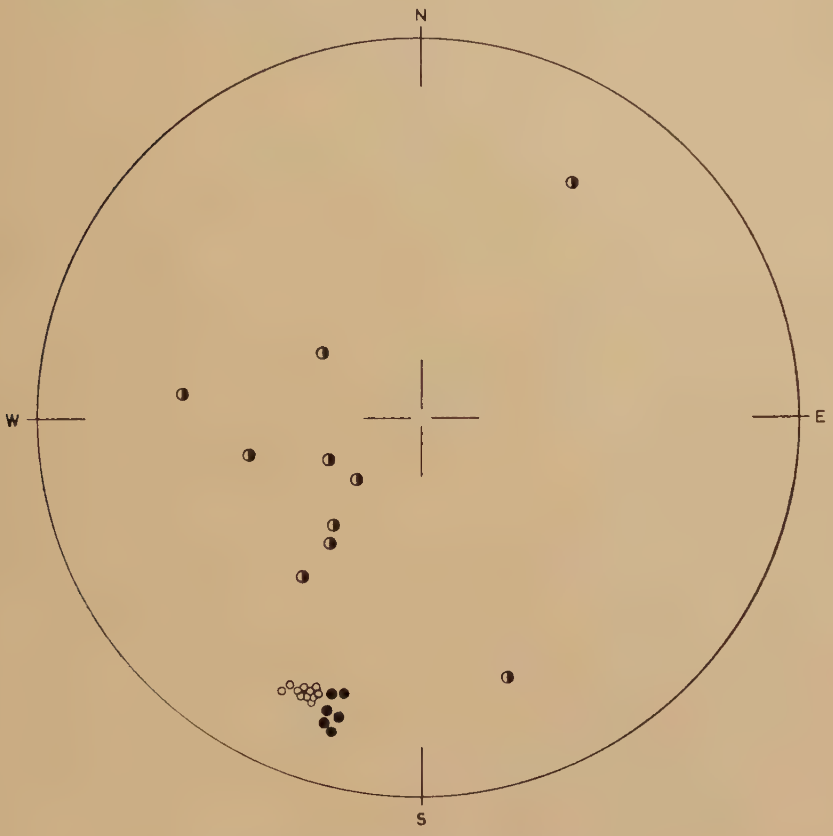
Fig. 3



Polar (equal area) projection. Reversal at Shatterford.
× Upward dip.
● Downward dip.

Incidental to these researches was the discovery, at Shatterford, of igneous rocks, from two sites about 200 yards apart, whose directions of magnetization are plotted in fig. 3. They fall into two distinct groups, one having a mean polarization N 30° E with a downward dip of 3°, and the other being magnetized N 215° E with an upward dip of 3°. The field evidence leaves no doubt that the rocks from both the sites belong to the same intrusion. The only possible explanation of this seems to be that the reversal must be due to some effect of the type postulated by Neel (1951). Heating tests performed so far in the laboratory give no indication that the mechanism of self-reversal has been preserved.

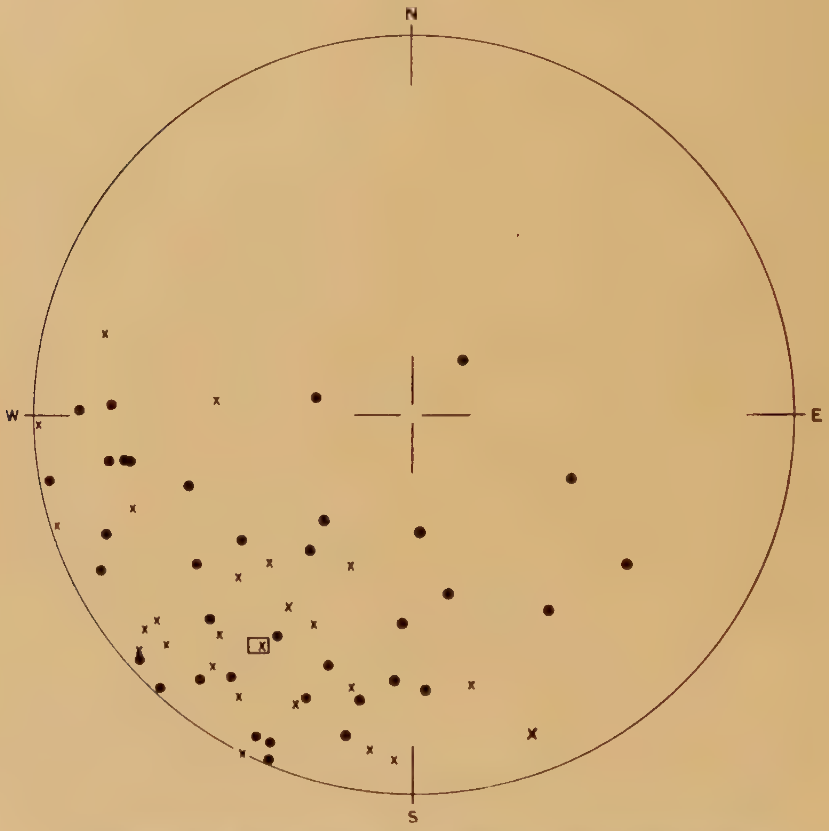
Fig. 4



Polar (equal area) projection.
Country and Contact Rocks at Clee Hills.
◑ Unbaked country rock. Mean intensity $1{\cdot}6 \times 10^{-7}$ e.m.u./g.
● Underlying contact rock. Mean intensity 100×10^{-7} e.m.u./g.
○ Overlying contact rock. Mean intensity 300×10^{-7} e.m.u./g.
All dips downward.

A second point of interest is that it was possible, from our measurement, to resolve a long-standing controversy as to whether four particular igneous bodies, exposed at sites between the Clee Hills and Walsall, are intrusive or extrusive in origin. For while T. W. Pocock (1931) considered them to be lava flows, C. E. Marshall (1942) suggested that they may be sills. We collected samples of the igneous rock and of the overlying and underlying sediments from each of these sites, and measured the directions of remanent magnetization. The results for one site (the Clee Hills) are shown in fig. 4. It is evident that while the unbaked sediments, from considerable distances away from the contact have scattered directions of magnetization, the rocks immediately above and below the igneous body are magnetized in similar directions, and have, moreover, a much higher intensity of magnetization. This seems to suggest strongly that they were both heated simultaneously, and therefore that the body is an intrusion. Similar evidence of intrusive origin has been found for the other three sites.

Fig. 5



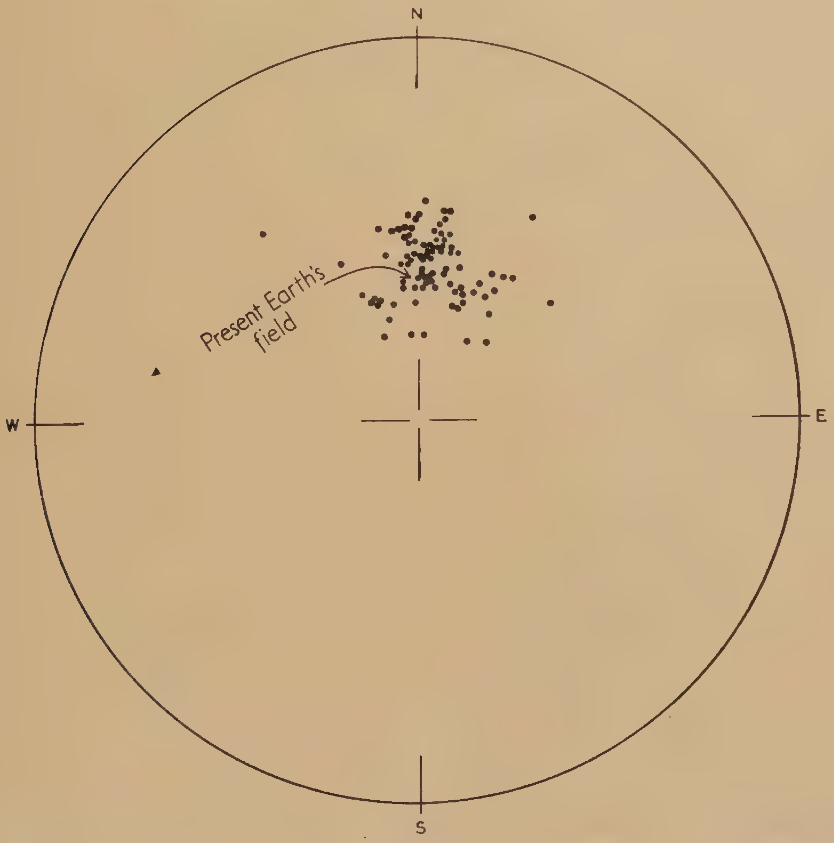
Polar (equal area) projection. French Triassic sandstones.
× Upward dip.
● Downward dip.
☐ Mean axis of British Trias (upwards).

§ 2. Triassic Sandstones from France and Spain

It has been shown previously (Clegg, Almond and Stubbs 1954) that the rocks of the New Red Sandstone System in England are consistently magnetized along a North East–South West axis, with shallow downward dips, suggesting that the British land mass has moved northward from close to the Equator, and rotated in a clockwise sense relative to the geographical poles, at some time since they were laid down. The measurements have now been extended to rocks of similar age on the continent of Europe.

Figure 5 shows the combined results of measurements on sandstones from seven sites in the Lower Trias of the Vosges region in France. It will be seen that the general North East–South West azimuthal direction of magnetization appears to persist on the Continent, although the scatter in direction is considerably greater than that observed in Britain, suggesting that the rocks may be only partially magnetically stable.

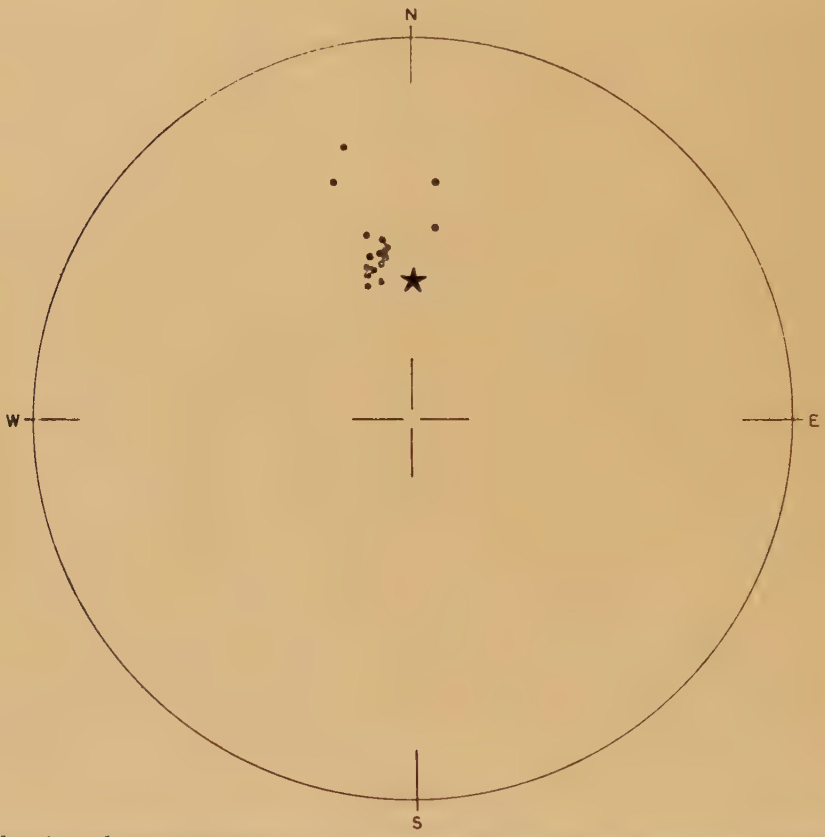
Fig. 6



Polar (equal area) projection. Triassic sandstones from Villaviciosa.
(Uncorrected for geological tilt of strata.)
• Downward dip.

In a paper published in 1954, S. W. Carey concluded from tectonic considerations that Spain may have undergone a rotation of some 35° in an anticlockwise sense during the Alpine orogeny, about a pivotal point situated at the Western end of the Pyrenees. It was considered that a comparison of the magnetic directions of the Triassic sandstones of Spain and Great Britain might test this theory ; for if such a movement has occurred, Spanish rocks of the same age should be polarized along a North–South axis. Rocks were collected from a total of seven sites in North and Central Spain, but unfortunately those from four of these localities proved to be magnetically unstable. Of the three sites showing consistent magnetization that at Villiaviciosa, on the North coast near Oviedo, was most extensively sampled. The results are plotted in fig. 6, and it is evident that the mean direction lies close to that of the present Earth's field. The plots have not been corrected for the geological tilt of the strata, which had a value of 30° and was directed within a few degrees of magnetic North, so that the magnetization of the samples when *in situ* would be almost vertically downwards. This suggests that the rocks possess some degree of magnetic stability. The magnetic

Fig. 7



Polar (equal area) projection. Triassic sandstones from Alcolea and Aguilar de Anguita. (Uncorrected for geological tilt of strata.)
• Downward dip.
★ Present Earth's field.

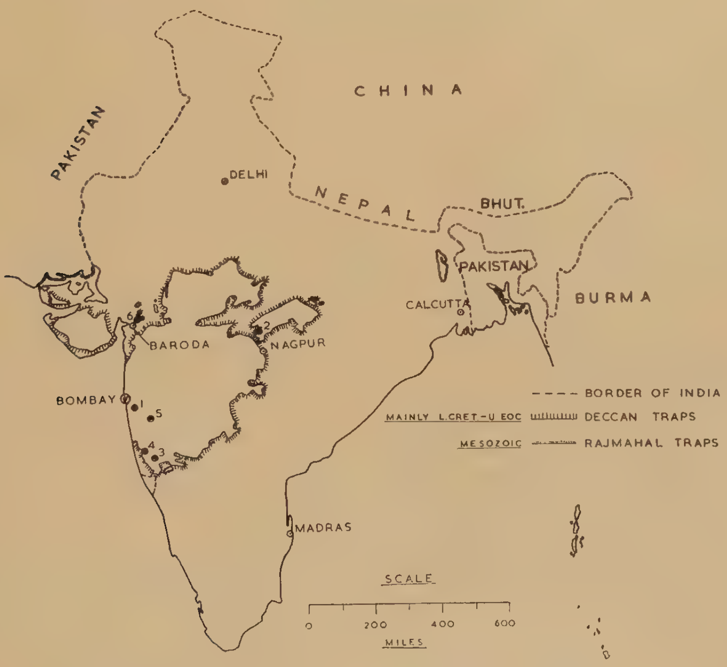
directions of rocks from two other sites, one near Alcolea in Central Spain and the other at Aguilar de Anguita nearby, are plotted together in fig. 7. They show similar polarizations, although the same test of stability cannot be applied to them since the strata were almost horizontal.

Comparison of these azimuthal directions of magnetization with those of the British Trias would appear to indicate that the postulated rotation of Spain has in fact occurred. However, since the mean magnetic inclination is approximately 25° steeper than that of the British rocks, while the mean latitude of the Spanish sites is some 10° farther South than that of the British, the final interpretation of the results remains inconclusive.

§ 3. Rocks from the Deccan Traps of India

Palaeomagnetic measurements on basaltic lavas from the Deccan Traps of Western India have been made previously by Irving (1956) who examined seven specimens from widely spaced localities, and by Clegg, Deutsch and Griffiths (1956) who obtained rather more than 400 specimens taken from two areas of limited lateral but considerable vertical extent, one in the neighbourhood of Khandala and the other near to Linga.

Fig. 8



Palaeomagnetic surveys (Deccan traps).
1, Khandala area. 2, Linga area. 3, Nipani area. 4, Amba area. 5, Kambatki Ghát. 6, Pavagadh area.

Both sets of measurements showed the mean magnetic direction to lie along a NNW–SSE axis inclined rather steeply upwards towards the North, corresponding to a pole position close to Florida. The work of Clegg *et al.* has now been extended to include the following four extra localities (see fig. 8) in the Deccan Trap system :

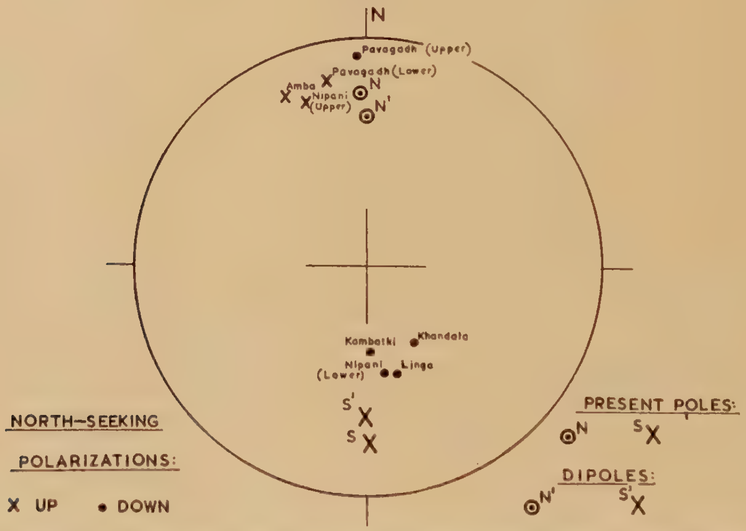
(*a*) the Nipani Area of Southern Bombay Province where specimens were collected from seven sites several miles apart ;

(*b*) the Amba area, close to Kolhapur City, where basalts were collected from the side of a ghat, over a range of elevations covering some 1500 feet ;

(*c*) the Kambatki area south of Poona ; and

(*d*) Mount Pavagadh, which rises abruptly 2400 feet above the surrounding plains to the north-east of Baroda in Gujerat. This hill is separated from the main body of the Deccan Traps by a distance of some 30 miles, and while on its lower slopes there are numerous exposures of horizontally bedded lavas typical of the Traps, these are overlain by 50 to 100 feet of acid tuffs, and capped by a massive plug or flow of rhyolite.

Fig. 9



Deccan traps. Directions at Bombay. Computed from mean results for various areas.

The mean directions of magnetization of the rocks from the various areas are shown in fig. 9 and are listed, together with other relevant data, in table 2. The results for the lower mainly basic flows and the upper acid rocks of the Pavagadh area have been treated separately, and the same procedure has been adopted for the lower and upper flows of the Nipani and Amba areas, where the higher have opposite polarizations from the lower. The magnetic directions for the original Khandala and Linga areas (Clegg, Deutsch and Griffiths 1956) are also shown in the figure.

Table 2

(1) Area	(2) No. of Speci- mens	(3) Intensity of magn. $\times 10^3$ c.g.s.u./c.c.	(4) Mean azimuthal direction α	(5) Mean Dip δ	(6) Radius of 50% circle of confidence
Kambatki	5	2·7	176°	+60° down	2·5°
Nipani (lower)	44	1·9	170°	+57° down	4·5°
Nipani (upper)	59	1·6	340°	−30° up	3·6°
Amba (lower)	54	3·1	141°	+59° down	4·1°
Amba (upper)	34	2·9	335°	−23° up	4·5°
Pavagadh (lower)	41	3·2	348°	−12° up	4·1°
Pavagadh (upper acid)	17	0·3	357°	+15° down	3·5°

It is evident that the present results are in broad agreement with those obtained previously by Clegg *et al.*, and that they are compatible with the assumption that the Indian sub-continent has undergone a substantial northward movement relative to the Earth's geographical axis at some time since late Cretaceous or early Eocene times when the rocks were formed. There is, however, a considerable difference between the mean magnetic directions found at the various sites. This is clearly illustrated in fig. 10, where the ancient pole positions corresponding to the values of α and δ given in table 2 are plotted, together with that given by Irving (1956).

It is interesting to note that the pole positions for the lower flows of the Nipani, Amba and Pavagadh areas lie farther from the present geographical pole than do those for the upper rocks. These discrepancies may evidently arise from one of a number of causes, viz :

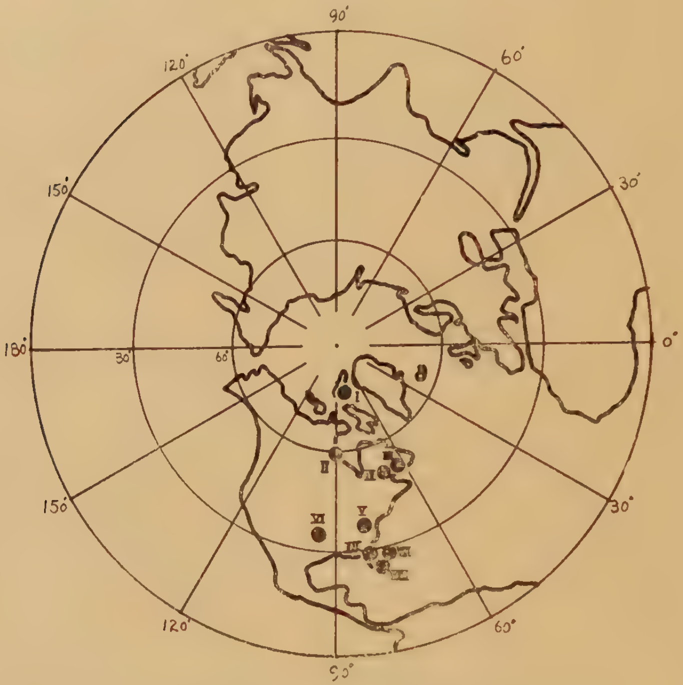
(*a*) They may be due to some physical phenomenon associated with different depths of burial, such, for example, as that described by Graham (1957).

(*b*) They may be indicative of partial magnetic instability, and the consequent pulling of the magnetic directions towards that of the present Earth's field. For rocks which are magnetized normally (N.N.W. with upward dips) this would tend to reduce the magnetic dip, and consequently to move the apparent position of the ancient pole northwards, while for those magnetized in the reverse direction it would have the opposite effect. It is worth noting that the four most northerly pole positions (Nos. 1, 2, 3 and 4 in fig. 10) were obtained from normally magnetized rocks, and that the remainder which lie at considerable distances from the present pole, are from rocks with reverse magnetization.

(*c*) They may represent a northward movement of India relative to the Earth's rotational axis, during the time when the Deccan Traps were being laid down.

This work is being further extended and a more detailed account and discussion of the results will appear shortly elsewhere.

Fig. 10



Ancient pole positions for various sites.

I, Pavagadh (upper). II, Pavagadh (lower). III, Amba (upper). IV, Nipani (upper). V, Linga. VI, Nipani (lower). VII, Amba (lower). VIII, Khandala. IX, Irving's (1956) pole position from seven sites.

ACKNOWLEDGMENTS

We wish to express our gratitude to Professor P. M. S. Blackett for his constant encouragement and advice. We are also indebted to numerous members of the staff of the Tata Institute of Fundamental Research, Bombay, for much generous help in the Indian work, and to the Director of the Institute, for permission to use the laboratory facilities there. Finally we wish to thank the Department of Scientific and Industrial Research for the award of grants to finance these researches. One of us (C.W.F.E.) is also in receipt of a maintenance grant from the same Department.

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Magneto-Geological Mapping in Iceland with the use of a Compass

By T. Einarsson
University of Iceland

The following is a report on the magneto-geological field work which Th. Sigurgeirsson and I have carried out in Iceland during the last 3 years. We have collected more details concerning the distribution of rocks of normal and reverse magnetization than it is possible to relate here. Some of the details that have to be omitted it would have been tempting to enter upon, but the limitation of space only allows me to give a summary of some of the main results of our studies.

For shortness I will speak of normal and reverse rocks when I mean rocks of normal and reverse magnetization.

When we have a young and fresh basaltic volcanic rock it is possible to determine in the field, by using a compass, whether it is normal or reverse. This has been shown previously by Einarsson and Sigurgeirsson (1955) and I will add only a few remarks here about the extension of the method to older rocks.

When, in Iceland, we proceed from younger to older rocks, which latter have formerly been buried under a thick cover of rocks now removed by erosion, we eventually come to a depth where the magnetization is faint and irregular. In the beginning of our work we thought that the compass method was not applicable in the older rocks. But later we found out that it was. We detected that the magnetization is clear and strong in the contact material of a lava flow. With contact material of a lava I mean the following: (1) an underlying sediment burnt by the lava, (2) red basal scoriae, (3) the lowest layer of the lava, 5–10 cm thick.

In these parts the magnetization is particularly stable and this has enabled us to penetrate without difficulty to our oldest, Tertiary lavas. We can easily imagine why in the contact material the magnetization is most stable. In the burnt sediment we have hematite with its high Curie point. In the red scoriae we have hematite and fine grain, and in the contact layer of the lava itself we have fine grain, much finer than in the main bulk of the lava.

A further difficulty which we have met in a very few cases is the magnetization induced by the present field in the piece of lava which is tested. But it is simple, to see whether induction plays a role, and, as a rule, it does not.

Our field work, then, consisted in testing the rocks by the compass method for their normal or reverse polarity. The main result can be formulated thus: In every part of the country so far studied and in old and young rocks there is a fundamental regularity in the magnetization. The normal and reverse lavas are not mixed in a haphazard way, they are arranged in well defined groups of alternately normal and reverse polarity and there is a clear and significant transition zone between successive groups. The transition is usually marked by a sediment or erosion form, indicating a time interval during which the change of polarity has taken place. But sometimes the transition takes place gradually in several lavas which have followed each other in a relatively rapid succession. This gradual turnover may be detected with the compass, but the details have been worked out by Sigurgeirsson with a magnetometer.

Further it may be noted that within each magnetic group we find various kinds of magnetic materials all with the same polarity. On the other hand we have not detected any systematic difference in volcanological or petrographical respect between normal and reverse groups.

It appears that this fundamental regularity is very naturally explained by reversals of the geomagnetic field. And in my view the fact that the transition from one group to the other is found to be of clear geological meaning, showing that the change of polarity takes time, is one of the important arguments for the hypothesis of field reversals.

The obvious idea now presents itself to map the magnetic groups with the compass method, and by combination of magnetic and geological work to get as long and detailed a record of the magnetic field as possible.

We have worked out, in various parts of the country, a number of successions of magnetic groups. The longest succession, or column, in eastern Iceland, has a height of about 6 km and contains 30 groups with the average thickness of 200 m. The column is not quite complete, and we estimate that the final number of groups will be about 40.

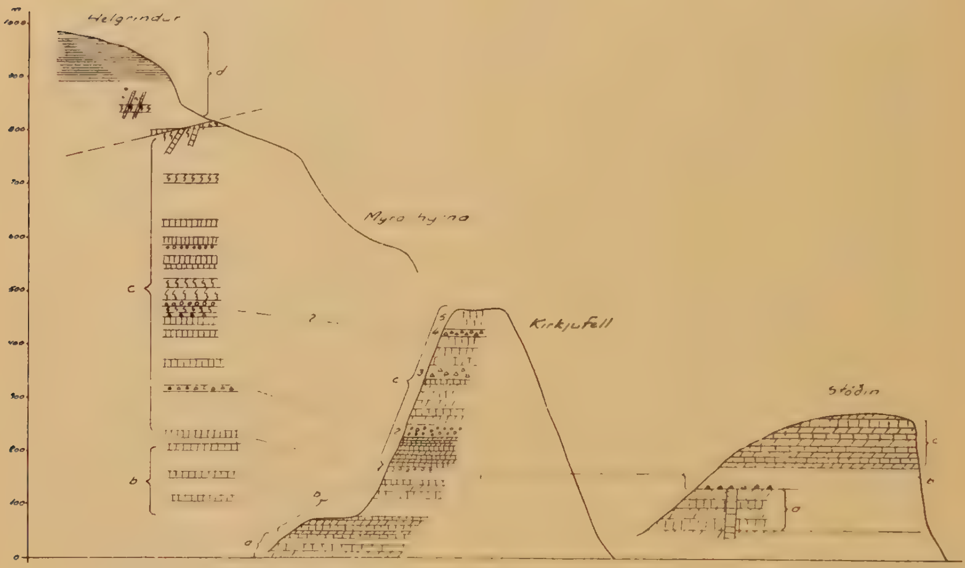
In western Iceland we have studied a column of thickness 4·7 km consisting of 13 groups with an average thickness of 340 m, but the thickness varies within wide margins. The total thickness of the normal groups here is 2175 m and that of the reverse ones 2250 m. The average thickness per group is 310 m for the normal and 375 for the reverse. The similarity of these figures is rather striking and is one argument against a volcanological difference between normal and reverse groups. In other parts of the country the columns are always shorter.

I shall now discuss a few sections, first two important sections of Quaternary rocks and then the succession of 13 groups I mentioned before.

SNÆFELLSNES (fig. 1)

We have here a section with fossiliferous sediments, whose age must be assumed to be near the Pliocene–Pleistocene boundary. We find a moraine on a striated floor, arctic marine fauna, and finally sandstone with plant remains that indicate warm climate, something near the present one (Pjeturss 1904, Askelsson 1938). The sediments rest unconformably on older basalts, which are mostly of higher Tertiary age. They are faintly magnetized, and of reverse polarity except at the very base of the section. Covering the sediments we have fresh basalts forming two groups, a lower reverse one, already found by Hospers (1953) and a higher normal one. In the lower group there are several horizons of sediments, some probably moraines and it is clear that the building up of the group took some considerable time, it was not poured out in just one volcanic spasm.

Fig. 1



The two Quaternary magnetic groups in Snæfellsnes.

Stödin : (*a*) Tertiary basalts of weak reverse magnetization, cut by a dyke ; (*b*) Interglacial sediments ; (*c*) Quaternary basalts of reverse magnetization. *Kirkjufell* : (*a*) Normally and (*b*) reversely polarized Tertiary basalts, weak magnetization ; (*c*) Quaternary basalts of reverse polarity. 1, 2, 3, 4 are conglomerates, 5 a partly brecciated thick lava. *Mýrarhyrna-Helgrindur* : (*b*) Tertiary basalts, weak reverse magnetization ; (*c*) Quaternary lavas and breccias of reverse polarity ; (*d*) Breccias, dykes, and lavas of normal polarity.

After the reverse group had been formed, erosion began and on a sloping erosional plane there rests the normal group.

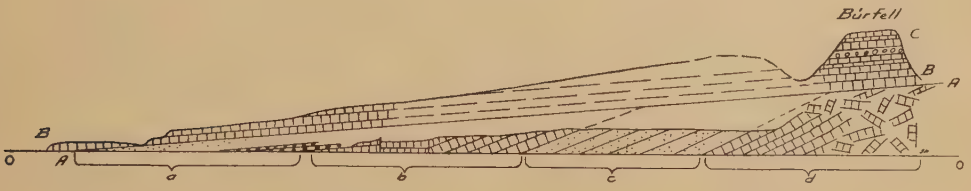
We find then two magnetic groups which can be considered as Quaternary. The lower one began somewhere near the Pliocene–Pleistocene boundary.

TJÖRNES (fig. 2)

In this locality, 320 km away from the one just described, there occurs Pliocene fauna and flora and here an attempt may be made to penetrate from the Pleistocene into the Pliocene. The youngest rocks, here of interest, form a sheet of fresh basalts, that covers shellbearing deposits at Breiðavík, in the north.

The sheet rises and thickens southwards and Búrfell (761 m) forms the highest and thickest part (130 m). These basalts form two magnetic groups, a lower reverse one that extends over the whole area, and a higher normal one, that is found in Búrfell. They are separated by a conglomerate of a few metres thickness. This sediment may represent glaciation.

Fig. 2



Pliocene and Quaternary rocks in Tjörnes.

O–O sea-level. *A–A* formerly horizontal plane on which the Quaternary basalt groups of reverse (*B–B*) and normal (*C*) polarity were deposited. (*a*) Sediments in Breidavik, marine sandstone on top, continental conglomerates below; (*b*) Disturbed succession of basalts, underlying (*a*) at one end and overlying conformably at the other end the Pliocene sediments (*c*); (*d*) basalts, much broken and altered.

The reverse basalts rest conformably on the deposits at Breiðavík. At the base of the fossiliferous clays there occur shells that indicate arctic conditions (Askelsson 1933–1934), but a higher sea-temperature not less than the present is inferred (Bárdarson 1925). The age is somewhere near the Pliocene–Pleistocene boundary, and we note the close parallelism with Snæfellsnes. In both places we have from below upwards cold climate, warm climate, then volcanism with, first, reverse and then normal polarity.

In both places also the sediments rest on an unconformity. But in Tjörnes we will see that the unconformity cuts Pliocene sediments and basalts. These marine sediments seem to be either middle or upper Pliocene but it is not possible to define the age more closely (Bardarson 1925, Weir, private communication†).

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† Dr. Weir, Glasgow, considered at my request in 1943 the age of this formation on the basis of the published material. He concluded " that most of it is Upper Pliocene, i.e. it corresponds to some part of the English Crags, excluding the Lower Pliocene (Diestian) Lenham Beds ".

The Breiðavík deposits rest on normal basalts, and normal basalts directly overlie the lower Pliocene sediments. In between there occur at places reverse lavas, but unfortunately the basalt series is so broken and faulted that we have not been able to trace here a continuous magnetic sequence. The unconformity naturally also is a serious hindrance.

MIDDLE WESTERN ICELAND

To get deeper into the Tertiary we now turn to middle western Iceland. In this area we have traced the individual magnetic groups over larger areas and so mapped them (fig. 3, Plate). This refers especially to the higher groups.

First we have here two groups, the present and Quaternary normal one, and an underlying reverse one, overlying a moraine. These two groups are naturally identified with those we have seen in Snæfellsnes and Tjörnes, and will be called Normal 1 and Reverse 1. The latter rests unconformably on plateau basalts, whose highest group is normal, and will be called Normal 2. This is not meant to imply that the magnetic record is here uninterrupted, only that this is the succession found here. Unfortunately it is not possible to estimate the interval between Reverse 1 and Normal 2 or whether there is here a major gap in the record. But starting with Normal 2 downwards, we have a long succession of magnetic groups where the record seems to be practically unbroken. This is a plateau of concordant lava flows of total thickness about 4·5 km and comprising 13 consecutive magnetic groups.

In the five topmost groups, or down to a depth of 1500 m in the plateau, there occur at intervals layers of conglomerate which are very similar to moraines and sometimes a striated floor is found, proving glacial action. On the basis of this these rocks have been thought to be of Pleistocene age. But in my view they must be Tertiary. I cannot here give my reasons but the question is important for it makes a difference whether there were 7 or only 2 magnetic periods during the Pleistocene.

At the bottom of the plateau succession, at the locality Hreðavatn, is found lignite that has been studied recently by Professor Schwarzbach and Dr. Pflug of Cologne (Schwarzbach 1956). The latter concludes that the lignite belongs to the Lower Tertiary. The average duration for the 15 magnetic periods is then maximally about 3–4 million years. But as there may be a large gap at one place, according to my assumptions, the maximum average duration is shorter than this.

I will now give a description of this Tertiary succession, and especially mention the sedimentary layers that separate the magnetic groups.

Normal 2 has a thickness of about 150 m. Considerable sediments are found within the group, with signs of severe weathering and two horizons indicating frost action are found. The group is separated from the underlying one by a 10 m thick sediment. The underlying reverse lava was broken up by frost and covered by mud with rounded pebbles. Then there is coarser gravel and fine windblown sand at the top. It seems probable that a few thousand years would suffice to explain this sediment but a closer estimate cannot be made.

Reverse 2 is about 300 m thick. Beside several thin layers of sediment there is one main horizon of sediments. Here are found up to 4 conglomerates of morianelike appearance. Considerable erosion is evident at places. Here is considerable time during which volcanism was nearly extinct. The group is separated from the next by a layer of moraine and windblown sand, and a glacially striated floor is found at places. A time of at least several thousand years is probably represented here.

Normal 3. This group is exceptionally thin, only about 50 m and less. The lavas of the lower part are especially thin and without sedimentary intercalations. They extend in reality into Reverse 3 and in them is found a gradual change from reverse below to normal polarity above. The details of this transition have been studied by Sigurgeirsson and will be discussed by him in the following paper.

Reverse 3. This group was at one place deposited against a mountain side and has therefore very variable thickness. But mainly its thickness is about 500 m, and appears to lie conformably on Normal 4, although this is difficult to decide. The group contains scattered sediments of a total thickness of about 150 m, and 3 main horizons of sediments are seen, two at least with glacial traces. Vestiges of erosion are also seen. We have here a few subgroups of lavas, separated by sediments, but each subgroup is practically without sedimentary intercalations. Each sediment is comparable with those that otherwise form boundaries between magnetic groups. We get on the whole the picture of a number of separate volcanic periods with only occasionally a shift of polarity in between, as is reasonable. There is certainly no strict parallelism between volcanic and magnetic periods in the sense that every new volcanic spasm is accompanied by shift of polarity. This is also clearly shown in Normal 1.

Reverse 3 is separated from the next group by a sediment 30–40 m thick. There is coarse conglomerate at the bottom, but else windblown sand and clay.

Normal 4 has a thickness of about 800 m. At one place we find a section of 600–700 m of lavas practically without any sediment. In another we have 30–40 m of conglomerate and sandstone near the top of the group. There is also here a horizon with vestiges of frost action, the deepest one we have found.

The lower boundary of the group is marked by a 30–50 cm layer of clay on an eroded lava surface.

Reverse 4 is about 200 m thick but is incompletely known. In a section with 7 lavas there are no sediments. The lower contact is invisible.

Normal 5 is about 500 m thick. No thick layers of sediments were found but several thin layers of sandstone. The lower contact is not seen.

Reverse 5 is about 1000 m thick. In this thick group the total amount of sediments is only about 50 m. In these sediments are found vestiges of disintegrated lavas. Such a disintegration should demand time of the order of 1000 years. In the middle part of the group there is a 12 m stratified conglomerate, probably transported by water. The stones show nearly exclusively normal polarization which is not surprising at this depth in the plateau. Further there is a white banded clay, probably a chemical deposit, which I have not noted at higher levels. This may indicate warm climate and we will soon reach a lignite horizon.

This group is separated from the next by ½ m of windblown sandstone on a worn lava surface.

Normal 6. Thickness about 200 m. Near the bottom there are a few metres of sandstone. The lower boundary is brown sandstone over 3 m thick, very probably windblown.

Reverse 6. Thickness about 100 m. It contains a 40 m sediment essentially windblown, but also with a disintegrated lava. The group contains about 10 lavas. The lower boundary is marked by a 10 m sediment, mainly white ‘ clay ’ and lignite.

Normal 7, *Reverse* 7 *and Normal* 8, of thickness 125, 150 and 350 m respectively, show no sediments, but good outcrops have so far not been studied. The boundaries are for the same reason still unsharp.

Below Normal 8 there is a group of lavas whose magnetization could not be detected, and 1–200 m deeper is the lignite horizon Hrefavatn, whose age is considered as Old Tertiary, as I said before.

Earlier I pointed out that the maximum possible average duration of a magnetic period was about 3 million years. This figure is probably still far too high. In most of the magnetic groups it seems impossible to find place for such long periods as several million years. Such intervals must leave their marks. Naturally it is not possible to estimate directly the duration of the individual magnetic periods, but considering the number of lavas, the time required for disintegration of uncovered lavas, the small thickness of sediments, and the scarcity of signs of erosion, I should say that ½ million years is a better estimate than 3 million years for the average duration of a period. But that the individual periods were of uneven duration seems also to be quite clear. The time taken for a reversal of the field is geologically very short. The boundary sediments or erosion forms do certainly not necessitate the assumption of a longer time than 10 000 years, and even a few centuries might in most cases be sufficient.

Whether it will be possible to deduce an unbroken magnetic record for most of the Tertiary in Iceland’s basalts remains to be seen. But it is already clear that the number of magnetic periods in the Tertiary was more than thirty.

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Direction of Magnetization in Icelandic Basalts

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In the previous paper T. Einarsson has given the results of a magneto-geological study, carried out with a field compass, which showed that groups of normal and reversed magnetic polarity, with respect to the present geomagnetic field, alternate in a regular geological sequence in the Tertiary and Quaternary basalts of Iceland. Following this field investigation, oriented samples have been taken for laboratory measurements.

The magnetization is measured on an induction magnetometer built by A. Brynjolfsson (described in following paper), in which a sample of 1–2 kg rotates at a speed of 5 revolutions per second. The direction of magnetization is determined with an accuracy of 1°. Measurements on magnetization are carried out both before and after partial demagnetization in an alternating field of 110 oersted amplitude.

For statistical treatment of measured directions of magnetization the method of R. Fisher (1953) has been used. The frequency density on the unit sphere is accordingly assumed proportional to exp ($k \cos \theta$), where θ is the angular distance from the true direction and k a measure of precision. The mean direction for N observations is the direction of the sum, R, of all unit direction vectors and the probable error, $\bar{p}$, for this direction is found from the equation

$$1-\cos \bar{p}=\frac{N-R}{R}\left(2^{1/(N-1)}-1\right).$$

The precision index, k, is calculated as

$$k=\frac{N-1}{N-R}.$$

To find the probable angular error of single observations, p, we use the equation

$$1-\cos p=\frac{\ln 2}{k}=\frac{N-R}{N-1}\ln 2.$$

Most of the samples are taken in the Hvalfjordur district, near Reykjavik, where the field observations have been carried out in greatest detail. The present material only covers the six latest magnetic groups, three of normal and three of reversed polarity. The samples are, as far as possible, taken from open profiles, where the geological structure is clearly visible. The sites for collecting samples have been chosen on basis of the magneto-geological field observations, and samples taken from within each magnetic group, as well as at the boundaries between groups of opposite polarity. Special attention has been given to places, where the field observations gave an indication of a gradual transition at the boundaries. In most cases only one sample was taken from each basaltic layer or lava bed. If more than one sample was taken the average value of magnetization is used here and treated as a single observation.

Samples from 33 lava beds belonging to the three groups of normal polarity show a distribution in directions of magnetization which corresponds to $k=38$ or a probable angular error for single samples amounting to 11°. Demagnetization reduces the probable error to 9°. Samples from 26 lava beds belonging to the three groups of reversed polarity show a distribution with a probable error of 24° before and 11° after demagnetization. The big scattering for the reverse magnetized samples in the natural state is probably partly due to isothermal remanent magnetization acquired in the earth's magnetic field. This secondary magnetization can even be so strong that certain samples from a reverse polarized rock formation show normal direction of magnetization in the natural state, but during demagnetization this turns to the regular reversed direction. A general feature for reverse magnetized samples is that the intensity of magnetization increases in the first stages of demagnetization. All this is easily explained by assuming an isothermal remanent magnetization which is less stable regarding demagnetization than the original thermoremanent magnetization. We therefore believe that in the demagnetized state the samples are in better agreement with the original magnetization than in the natural state, and from now on we only report results of measurements on demagnetized samples.

The measured direction of magnetization is corrected for geological dip, which in most cases is 4° or less. This direction is then interpreted as the direction of the geomagnetic field at the time when the rock was formed. Assuming that this field was a dipole field, we then calculate the geographic position of the magnetic poles, using the relation

$$\mathrm{tg}\,\phi=2\cot I$$

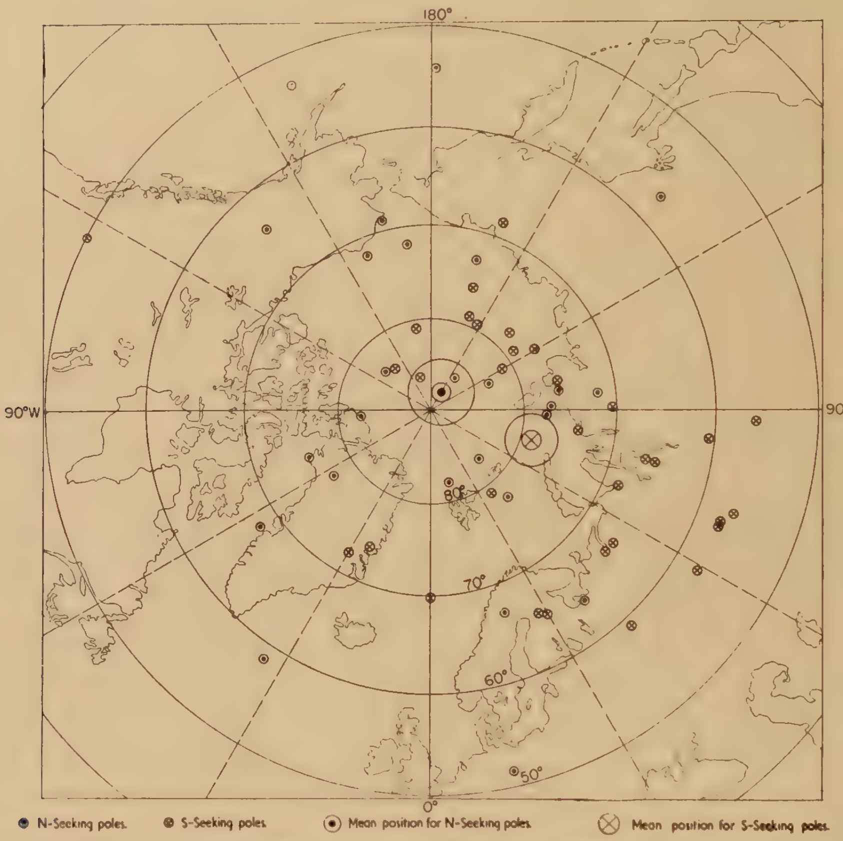
where ϕ is the angular distance to the south magnetic pole and I the magnetic inclination, positive for downward field directions and negative for upward directions. Instead of declination and inclination we then use the geographic position of one of the magnetic poles to represent the direction of magnetization in the samples. This seems to be a reasonable representation as it facilitates the comparison of results obtained at different parts of the globe.

In fig. 1 we see the results of measurements on 33 samples of normal and 26 samples of reversed polarity. For normal samples the positions of south magnetic poles are indicated by crosses, but for reversed samples positions of north magnetic poles are shown as dots. The magnetic poles are distributed around the geographic pole down to a latitude of 50°.

For south magnetic poles the distribution corresponds to $k=19$ or a probable error of $p=17°$. The corresponding values for north magnetic poles are $k=15$ and $p=18°$.

To compare this picture with the present geomagnetic field, the dipole formula has been used to calculate positions of magnetic poles from geomagnetic data of 20 magnetic observatories scattered over the earth.

Fig. 1


180°
90°W
90°E
0°
80°
70°
60°
50°
● N-Seeking poles
⊙ S-Seeking poles
⊙ Mean position for N-Seeking poles
⊗ Mean position for S-Seeking poles

Distribution of paleomagnetic poles. ⊗ south-magnetic pole. ○ north-magnetic pole. The big marks show average positions with their probable errors drawn as circles.

The scattering of these poles due to present anomalies in the earth's field corresponds to a probable error of 8°. In the course of time the magnetic field is believed to change in such a way that the geographic pole is the average position for the magnetic poles. To get a measure for the expected scattering of magnetic poles over long time intervals it is therefore reasonable to choose the geographic pole as a centre for the distribution. This results in a probable error of 12°. As the scattering in the paleomagnetic data is 50% greater than this, it might either mean that the present deviation of the magnetic pole from the geographic pole is less than average, or that our results show a greater scattering than corresponds to the state of the geomagnetic field in the past. If this is the case the scattering might perhaps be reduced by improved sampling, measuring or selection technique. Here no selection has been made and all measured samples are included in the results. By leaving out samples that have suffered big changes in magnetization during demagnetization, some reduction in the scattering of reversely magnetized samples can be obtained, but at the same time the number of valid samples is reduced so much that the accuracy of the average direction is lowered.

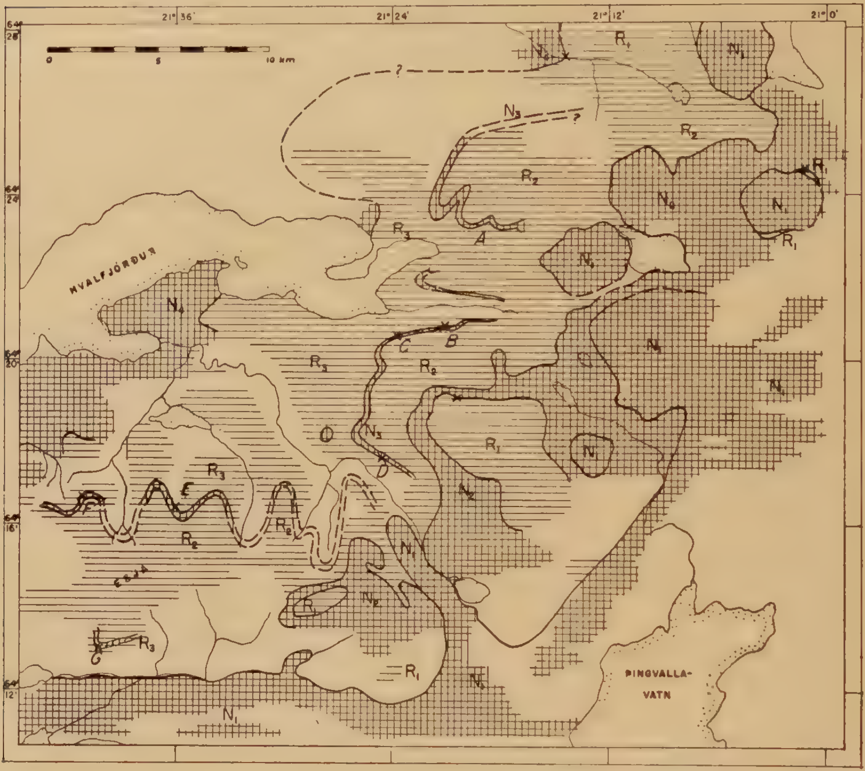
The mean position for all south magnetic poles is 73·9° E, 77·3° N with a probable angular error of 2·8°. We thus find a statistically significant deviation of the average south magnetic pole from the geographic pole. The average position for all north magnetic poles is 149° E, 87·8° N, with a probable error of 3·6°, in good agreement with the geographic pole as a centre for the distribution. Such agreement has also been found by Hospers (1954) in Icelandic Tertiary basalts of both polarities.

In order to investigate the origin of the deviation the results have been divided into the 6 magnetic groups. Only one of these groups, the oldest normal group, N_3, shows a significant deviation from the geographic pole. This group, however, is rather thin and only contains a small number of basaltic layers. It is therefore possible that the actual number of independent samples is not as great as assumed, and furthermore it is likely that some of these samples are from the very beginning of this normal period when the directions of the magnetic field may have been somewhat abnormal. For these reasons the observed deviation of the average magnetic pole from the geographic pole may not be the result of a polar wandering. This will first become clear when older samples are measured.

Figure 2 is a magneto-geological map of the area where most of the samples were taken. It is a part of T. Einarsson's map showing the Hvalfjordur district. The thin N_3 group stretches over most of this area. In seven places, marked with the letters *A* to *G*, samples have been collected. In all these places intermediate directions of magnetization were found at the lower boundary of the N_3 group. These intermediate directions make large angles with the present direction of the magnetic field and correspond to a magnetic pole in the neighborhood of the equator. In four more places intermediate directions have been found at the N_4–R_3, R_2–N_2 and N_2–R_1 boundaries. Three of these places are shown as crosses on the map, but one of them (R_2–N_2) is outside this area. We here use the term ' intermediate direction ' only for directions of magnetization which correspond to a magnetic pole with a latitude lower than 50°. Such intermediate directions have not been found within a magnetic group, but only at the boundary between two groups of opposite polarity. Even at such boundaries it is rather exceptional to find intermediate directions. In most cases the magnetic groups are sharply divided, with the abrupt change in polarity occurring across a thin bed of sediments.

Altogether intermediate directions have been found in 45 lava beds. This number, however, is no measure for the frequency of occurrence of these directions in the basaltic rock formation, as samples were preferably taken at places where the field studies had given some indication of an intermediate direction. A rough estimate indicates that rocks having intermediate directions of magnetization may amount to a few per cent of the total rock formation.

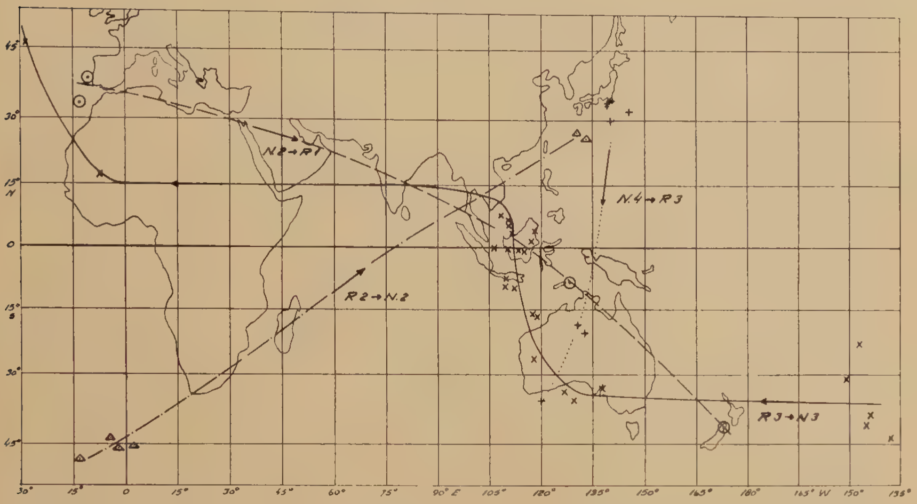
Fig. 2



A magneto-geological map of the Hvalfjordur district.

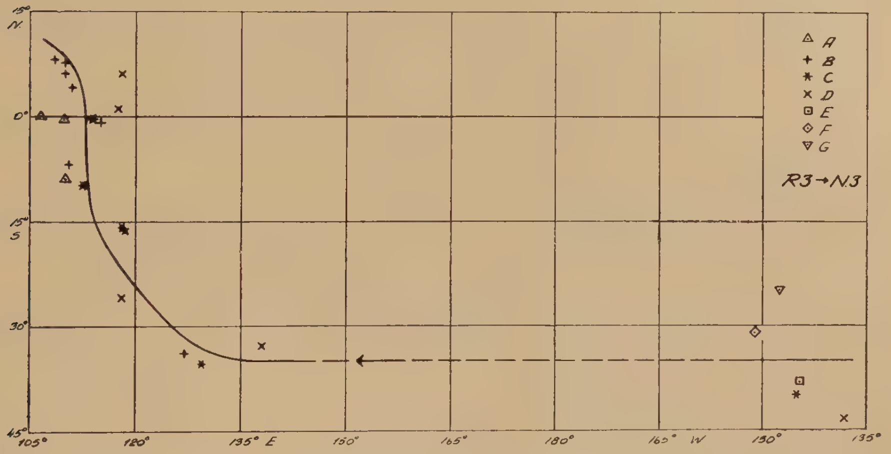
The results of measurements on samples showing intermediate directions of magnetization have been treated in the same way as for the other samples. The direction of magnetization is corrected for geological dip and geographic position found for the south-magnetic pole of the corresponding dipole field. Figure 3 shows the calculated positions of south-magnetic poles corresponding to all the 45 intermediate directions. The results from each of the four transitions are distributed rather regularly, indicating a definite path followed by the magnetic pole during the reversal of the magnetic field.

Fig. 3



South-magnetic poles corresponding to intermediate directions of magnetization found at four different boundaries between magnetic groups.

Fig. 4



South-magnetic poles corresponding to intermediate directions of the R_3–N_3 transition.

Only the R_3–N_3 transition has been studied in any detail. Figure 4 gives the results of 24 determinations from this transition on samples taken at the seven locations marked from *A* to *G* on the map. These places are spread over a distance of 25 km. All these results fall on a smooth curve to within 10° and the sequence of points along the curve agrees with the position of the samples in each profile. It seems reasonable to assume that this curve represents the transition of the geomagnetic field from the reversed to the normal direction. It is difficult to make an estimate of the time taken by this transition, but from the appearance of the basaltic layers, without any sediments between them, we should not expect that the time could be more than a few thousand years or even shorter.

Our results show some indication of a reduced field strength during reversals of the magnetic field. The mean magnetization of all normally and reversely magnetized samples is about 2×10^{-3} e.m.u./g, while for samples showing intermediate directions it is only half as much. Individual variations are, however, quite large so this can, in the best case, only give a very rough idea about the strength of the magnetic field. According to W. Elsasser (1956) the dipole term of the geomagnetic field should disappear during reversals. All we can say is that our results do not disagree with this statement.

If the dipole field disappears and only higher order harmonics are left during reversals we can not expect world wide agreement for the route of the calculated magnetic pole, but the intermediate directions may still prove quite useful for establishing geological correlations over large distances. The fact that we have found intermediate directions at 4 boundaries out of 6 in our investigation gives reason to believe that intermediate directions of magnetization will also be found in other basaltic regions. Correlation with sediments might also be a possibility. Some difficulty for this type of geo-chronological correlation might be caused by the apparent tendency of the calculated pole to pass the equator in a certain region.

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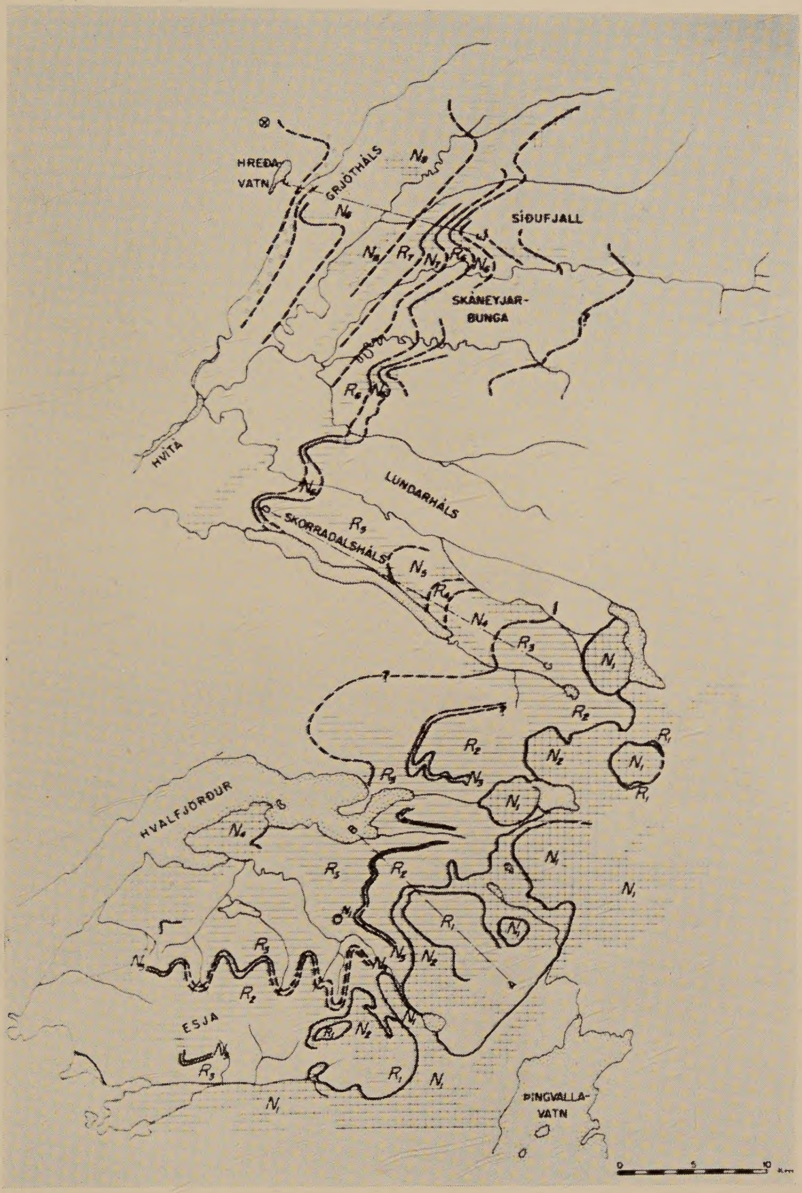
Fig. 3



Map showing distribution of magnetic groups of basalts in Middle Western Iceland. *N* (crosshatching) means normal, and *R* (horizontal hatching) reverse polarity. Crossed circle indicates the lignite locality of Hredavatn.

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